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Innovations in Antenna Designs Based Artificial Materials for Modern Applications

THESIS BOOKLET

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1 Abstract

In the last decades, the design of antennas based on artificial materials have been attractive for the attention of the *Radiofrequency (RF)* and microwave engineering communities due to the excellent inherent properties which can meet the urgent requirements of the current wireless technology. Artificial materials such as metamaterials are synthesized by embedding specific inclusions in host media. The purpose of the artificial materials structures design is to interact with and control electromagnetic waves that does not occur in natural material. However, my dissertation focuses on using artificial materials structures for modern antenna applications, including wearable devices, *multiple input multiple outputs (MIMO)*, *Global Positioning Systems (GPS)*, and self-powered systems. The *electromagnetic bandgap (EBG)* is artificial material with superior properties that can be applied to antennas. The feasibility of using the EBG structure-based microstrip patch and monopole antennas operating in the microwave range is demonstrated first. The artificial materials approach examines the use of EBG structure in the antenna applications. In the first application, the use of EBG structure to improve the directivity and gain of the planar microstrip antenna is explored. A gain enhancement has been achieved by placing the EBG lenses on top of the microstrip antenna. The proper position of these lenses and their separation are identified using ray tracing and classical optics. The second application involves the design of a monopole antenna based on an array of EBG structures with the partial ground plane for gain enhancement and directing antenna radiation from the boresight to the end-fire direction. The third application involves the design of a MIMO antenna based on an EBG structure with a partial ground plane to improve the mutual coupling reduction between the radiating antenna elements. For phase and frequency reconfiguration with high antenna gain, a reconfigurable antenna based on an EBG structure was utilized in this dissertation for the fourth application.

Reconfigurable antenna approach in wireless communication technology is utilized in two antenna applications. The first application involves *Direct Antenna Modulation (DAM)*; I explored the modulation process of electromagnetic signals in the antenna circuit design directly. In order to perform a *Differential Phase Shift Keying (DPSK)* modulation, two identical antennas are fed by a two-branch microstrip line with a phase shift of 180°. The designed antenna is further investigated to realize the effects of radiation leakage from the antenna elements on the human body in the context of wearable applications. This antenna design also is conducted to the antenna performance when it bent on a cylinder surface and compared to the flat case on four human body regions: arm, head, thigh, and chest. The proposed antenna also invoked EBG structure to improve the antenna gain. The second reconfigurable antenna application involves using an *ultra-wideband (UWB)* monopole antenna structure based on semiconductors devices as switching devices such as *Positive-Intrinsic-Negative (PIN)* diodes for reconfigurable band notch characteristics. The proposed antenna design is comprised of a modified circular patch and a partial ground plane. The notched band characteristics are achieved by etching a slot on the partial ground plane and

inserting three PIN diodes into the slots to adjust the antenna bands. Depending on the state of the diodes, the proposed antenna can operate in *Ultra-wideband (UWB)* mode, dual-band modes, or triple-band mode. The proposed reconfigurable antenna was numerically developed by invoking EBG structure for frequency reconfigurability and improve the antenna gain. The proposed antenna uses an EBG structure of circular *Split Ring Resonator (SRR)* unit cells based on 18 PIN diodes to achieve the required antenna features of frequency reconfigurability and high gain. Depending on the EBG configuration states based on 18 PIN diodes, the proposed antenna can operate in triple, quadruple, and quintuple operating bands.

2 Introduction

Novel antennas were recently published by utilizing various metamaterial and EBG structures [1] and [2]. Metamaterials are artificially structured to be engineered periodically to control *permittivity* (ϵ) and *permeability* (μ) over certain frequency bands that are not found in nature [1]. Metamaterials are invented to exhibit unique properties such as negative ϵ, negative μ and negative refraction index at the same frequency band. The responses of the material to the electromagnetic radiations properties can be described electrically by their constitutive parameters as seen in Fig.1. *Right-Hand Materials (RHM)* are called materials with positive, ϵ and μ, and those with negative ϵ and μ are called *Left-Hand Materials (LHM)* [3]. A negative structure of ϵ is considered a plasma, such as an array of wires [4]. In contrast, a negative μ structure, such as *Split Ring Resonator (SRR)*, is referred to as a gyro-tropic material [5]. The structure is called EBG, such as *Photonic Band Gap (PBG)*, whether both ϵ and μ are zero or very close to zero [6].

Metamaterials can be engineered based on a transmission line approach by applying non-resonant inclusions over a broad bandwidth [8] or based on the effective medium theory [9] by optimizing a unit cell with resonant structures over a relatively narrow bandwidth. The affective dimension of the period, or unit cell, must be much smaller than the *guided wavelength* (λ_g) at which the desired properties exist. Metamaterials must be dispersive in order to reach negative values of ϵ and μ; otherwise, they will not be causal [10]. The performance of metamaterials-dependent antennas is constrained by dispersion in the constitutive parameters. SRRs are an example of a gyro-tropic structure that, as described in [11], provides negative μ [12]. By printed arrays of wires or traces on substrates, negative ϵ can be achieved. Some of the studies published in [11] and [13] are focused on the use of these inclusions, such as SRR, to minimize diffraction from finite-ground planes and strong mutual inductive and capacitive coupling between antenna components among a variety of applications [13]. EBG structures of electromagnetic properties of ϵ and μ equal to zero or close to zero, metamaterials with a *zero-index* ($n = 0$), are capable of achieving highly directive antennas [14] with improved bandwidth [15] and size reduction [16]. The PBG lens is one of the common EBG structure categories [14]. Such structures can be built from

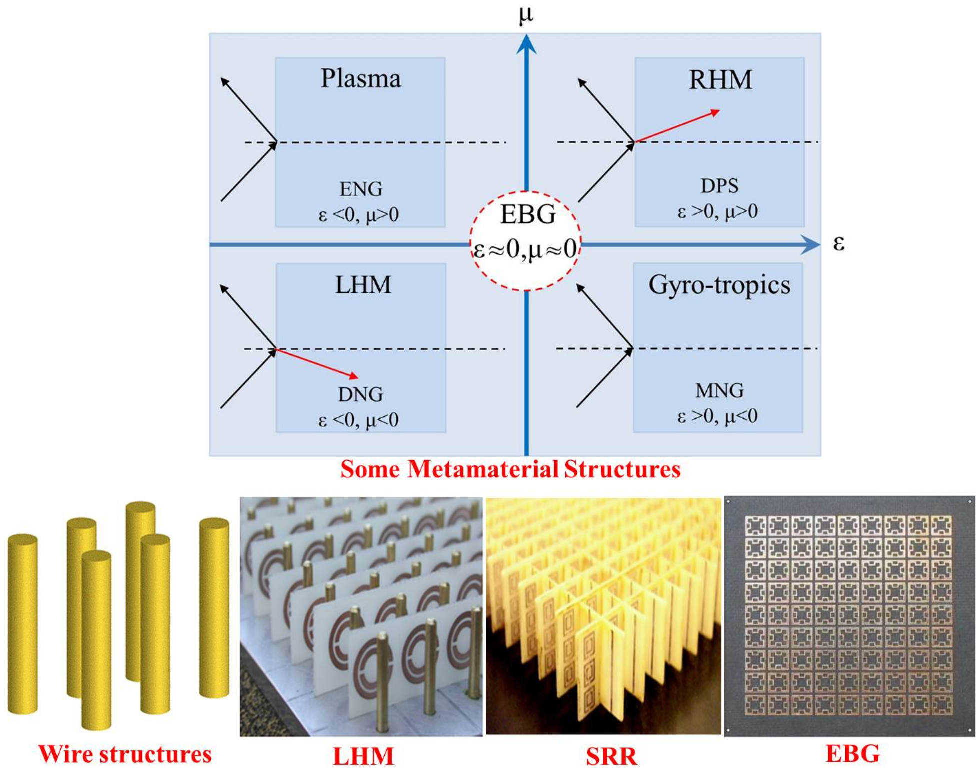


Figure 1: Metamaterials nomenclature based on the magnitude of the real parts of the ϵ and μ [7]

planar aperture arrays called *Uniplanar Compact PBG (UC-PBG)*. As in [7], [17] and [18], for antenna gain enhancement, their applications are expanded. However, some of the reported designs of UC-PBG/antenna suffer from intense backward radiation that reduces the *Front-to-Back ratio (F/B)* [14] and [15]. Furthermore, the studies [16]- [18] did not elaborate on the design strategy those results in the best PBG structures position. A zero-order resonance antenna was achieved using EBG structures [6] and [19]. In such media, the guided wavelengths are nearly infinite with independent patch physical dimensions to produce antennas much smaller than a half-wavelength. Such antennas show zero-order modes with uniform current distribution to reduce overall losses to result efficient antenna. The authors in [6] and [19] published an experimental validation of these properties. A *Frequency Selective Surface (FSS)* is another EBG structure type that is designed as a periodic array structure [20]. A spatial filter of periodic arrays of metallic elements on a dielectric substrate was defined as the FSS [21] and [22]. FSS designs were limited to bulky devices such as radomes for antennas and *radar cross-sections (RCS)* due to their complexity and sensitivity over a specific frequency range [23] and [24]. Implementing FSS structures, according to the authors in [25] and [26], could improve the antenna characteristics. For example, the authors in [27] used a transmission line model to reduce the unit cell size of the FSS structure. When the metamaterials structures are combined with another structure with oppositely-signed constitutive parameters, they exhibit unusual properties. As a result of the complementary interfaces that fill single negative and double negative metamaterials with conventional materials, the size of the antennas can be reduced [28]. Covering an electrically small dipole, which is not an effective radiator, with a negative permittivity shell results in a more efficient radiator, according to [28].

Due to the rapid developments in current wireless communication and information technologies, different reconfigurable antennas were established as alternatives to the conventional antenna design [29]. Reconfigurable antennas show rapid growth in wireless communication technologies to provide advanced features limited to conventional antennas. Furthermore, integrating reconfigurable antennas with other communication devices produces new applications such as flexible and dependable development solution, allowing antennas, wireless sensors, solar cells, smart clothes, and wearable microwave devices [30]. For multiple purposes, new antennas with the desired frequency bands are required. Reconfigurable antennas based on active electronic devices usually are applicable to tune frequency bands, radiation patterns, and polarization [31]. Such advancements provide more capabilities to resolve the complexity of the wireless communications [32]. As a result, researchers have been attracted to the use of reconfigurable antennas to improve the performance of wireless communication systems in differenet applications [33]. However, the main challenges in such technologies are: Integrating antennas with modern high-speed semiconductors while maintaining size miniaturization and achieving high gain-bandwidth over the frequency band of interest [34]. As a result of that, the antenna characteristics isolation from the communication system, high-speed semiconductor switching devices is the antenna's key objective [35]. RF switches such as *Microelectromechanical systems (MEMS)*, varactor diodes, transistor switches, and PIN diodes have been utilized by several researchers to enable frequency, pattern, and polarization reconfigurability in current and future wireless communication systems [36] and [37]. The authors in [36] and [37] described reconfigurable antennas based on polarization, radiation patterns, and frequency by integrating PIN diodes, RF MEMS, and varactor diodes into a system platform as switches to control the desired polarization and radiation direction, as well as the frequency operation bands. For frequency reconfiguration, the authors in [38] used PIN diodes as switches on a monopole antenna. A circularly polarized antenna based on an EBG array was proposed in [39] for frequency and polarization reconfiguration techniques. The authors in [40] discussed an antenna design based on a single PIN diode integrated into a folded slot patch on a flexible substrate for frequency and polarization reconfiguration.

Several approaches based on the DAM process are developed as alternatives to conventional modulation approaches due to rapid developments in today's information technologies [29]. DAM can be used to solve problems in modulation systems, such as the inevitable high-cost, high-complexity transmitter design. As a result, DAM has emerged as a practical solution for overcoming those modulation systems' limitations [36]. DAM is based on the idea of enabling carrier wave modulation in the antenna system [41]. Various DAM methods based on an array of switchable passive reflectors were proposed [42]. These techniques are well suited to dealing with the increasing complexities of wireless communications [32]. Renewable and non-conventional systems, unlike traditional electromagnetic devices like antennas, can be manufactured locally and are well suited to emerging technologies in communication and information technology [43]. The uses of transitional technologies to integrate antenna design and semiconductors are helped the rapid growth of wireless networking markets; however, this merger also necessitates innovative antennas to resolve such problems, such as design complexity and size reduction [44]. As a result, reconfigurable antennas have invoked much interest in the latest wireless communication technologies, particularly for 4G and 5G [33]. Reconfigurable antennas are being investigated to enhance the performance of wireless networking networks in a variety of applications [33]- [43]. Two PIN diodes were used as switching circuits in the antenna presented in [45] to directly control two binary *Phase Shift Keying (PSK)* modulated signals. For the DAM UWB transmitting antenna, three *Schottky diodes (HSCH-5330)* were used as switching devices in [46]. The authors in [47] designed a circularly polarized *Quadrature PSK (QPSK)* modulated signal using two orthogonal antennas. For *Terahertz (THz)* communication, a switchable FSS based on *Amplitude-Shift Keying (ASK)* modulator was presented in [48]. Carrier of RF DAM was investigated in [49] as a reconfigurable FSS-based phase modulator for the *Internet of Things (IoT)* applications. In [50], the *Intersymbol Interference (ISI)* of a DAM *On-Off Keyed (OOK)* signal-based narrowband transmitter antenna was investigated. Finally, using a transmitter based on programmable metasurface, the authors in [37] demonstrated 8-PSK modulation with 8×32 phase unit cells.

3 Original Contributions

In the following, I highlight five main challenge groups. Therefore, in this section, the original contributions of this dissertation are listed.

1-Metamaterial antenna structure based on a single EBG layer is presented to improve the antenna gain and aperture efficiency. A significant gain enhancement is achieved of five different microstrip antennas; in which the gain is enhanced from 5.6dBi to 11.1dBi at 2.45 GHz for the first design. The second design shows a gain enhancement from 6.3dBi to 13.4dBi at 2.45 GHz. The third design gain enhancement is found to be from 3.4dBi to 8.95dBi at 5.2 GHz. For the fourth antenna design the gain enhancement from 1.5dBi to 11.2dBi at 5.8 GHz. The last microstrip antennas design an improvement from 1.8dBi to 11.4dBi in antenna gain has been achieved at 5.8 GHz. On the other hand, the antenna aperture efficiency improvement is seen about 15%, 37%, 31%, 35%, and 26%, respectively, for the first, second, third, fourth, and fifth antenna design compared with their corresponding conventional microstrip antenna.

2- A printed monopole antenna based on EBG array is introduced to enhance the gain and orient the antenna radiation, mainly to the end-fire directions. The proposed antenna shows end-fire radiation patterns with a gain of $2.88 dBi$ and $5.8 dBi$ at 1.85 and 3.3 GHz, respectively.

3- A printed rectangular array of two slot microstrip antennas spaced with an EBG structure of low mutual coupling is proposed in [51] for the MIMO applications. The separation distance between the antenna elements is found to be about$\lambda_o/16$ with low mutual coupling of −29 dB at 2.45 GHz and −25 dB at 5.8 GHz. The antenna array structure is folded on a cylindrical substrate to suit wearable MIMO systems. The MIMO antenna performance has been improved in terms of *Envelope Correlation Coefficient (ECC)*, *Diversity Gain (DG)*, *Total Active Reflection Coefficient (TARC)*, *Mean Effective Gain Difference (MEG)*, and *Channel Capacity Loss (CCL)* after introducing the EBG structure with the proposed antenna array. A reduction in ECC to about 0.0005, the value of DG is touching $10 dB$, $TARC$ less than 0.25, MEG is touching 0 dB, and CCL is less than 0.2 ($bits/sec/Hz$) for the two operating frequency bands are achieved after introducing the EBG structure.

4- The modulation process of the electromagnetic signal is introduced to the antenna circuit design directly. For such technology, a planar and folded antenna profile is presented [52]. The proposed antenna is consistent of two patches with the same geometry for the DPSK process. The antenna is mounted on a flexible substrate for wearable applications. The proposed antenna consists of two non-concentric elliptical patches for broadband applications to suit the spread spectrum applications. The patch structure is fed with a 50 Ω microstrip line network of two branches and delayed by a phase shift of 180° at different frequencies. The phase shift of the RF signals is controlled based on two PIN diodes through a transmission line network located between antenna elements. The proposed antenna performance on the human body is subjected to bending and compared to the flat profiles. The patch size is reduced to suit wearable devices; therefore, a cylindrical substrate is introduced for bending. The proposed antenna design shows a gain of 4.73 dBi and 2.5 dBi for the planar and folded antenna profiles, respectively. The antenna is furtherly investigated to realize the effects of radiation leakage from the antenna elements on the human body in the context of wearable applications. The study is conducted to the antenna performance when bent on a cylinder and compared to the flat case on four human body regions: arm, head, thigh, and chest. The proposed antenna based on an EBG array is introduced to enhance the antenna gain. The proposed antenna achieved peak realized gain of 4.15 and 4.73 dBi at 5 GHz for the two PIN diode state without EBG structure; however, with integration of EBG with the proposed antenna, the antenna gain increased to 7.5 and 8.6 dBi, respectively.

5- A novel UWB monopole antenna structure with reconfigurable band notch characteristics based on PIN diodes is proposed. The antenna is compacted to provide a low cost, light weight, easy to control the bandwidth and frequency notch UWB antenna. The proposed antenna is comprised of a modified circular patch and a partial ground plane. The proposed antenna is designed to cover the entire UWB spectrum from 1.7 GHz to 11 GHz. The frequency reconfiguration is achieved in such antenna by adjusting the effective electrical length of the ground plane slot. The desired operating bands is achieved by etching a slot on the partial ground plane and inserting three PIN diodes into the slots. The reconfigurability is employed by adding three PIN diodes to obtain eight states with UWB, dual and triple operating bands. It could be obtained by changing the PIN diode state from ON-OFF and vice versa. Due to the simplicity of the biasing circuit and the best simulation with minimal gain degradation, radiation efficiency, and frequency band switch have been obtained when integrated the PIN diodes into the ground plane instead of a radiating patch. The frequency reconfiguration is accomplished by adjusting the effective length of the ground plane slot. To improve the antenna gain and control the operating frequency bands the proposed antenna based on an EBG array is utilized. The antenna gain has been improved about 4 dBi for all operating frequency bands after introducing the EBG structure. Frequency reconfigurability based on the EBG structure can be achieved by adjusting 18 PIN diodes integrated with the inner and outer SRR rings of EBG structure to switch between different operating bands including triple, quadruple, and quintuple.

The band-notch is achieved by etching a slot on the partial ground plane and inserting three PIN diodes into the slots for adjusting the antenna band. The reconfigurability is employed by adding three PIN diodes to obtain eight states with UWB, dual, and triple operating bands. It could be obtained by changing the PIN state from $ON-OFF$ and vice versa. Due to the simplicity of the biasing circuit and the best simulation with minimal gain degradation, radiation efficiency, and frequency band shift have been obtained when integrated into the PIN diodes. The frequency reconfiguration is accomplished by adjusting the effective length of the ground plane slot.

4 Motivations and Research Objective

With continuing demands for new antenna designs to satisfy the requirements of the most urgent applications researcher invoked many technologies to maintain the antenna developments. Some the developments includes wearable devices, implantable medical devices, MIMO and UWB systems. Such of these developments is the bandwidth enhancements for high data rates combined with the size and weight reductions for portable wireless devices in modern communication networks. However, gathering the desired antenna performance with the current developments generally limits the continuation of the wireless communications industry. It is because the conventional microstrip antennas suffer from several limitations such as narrow bandwidth, low efficiency, modest gain, low power handling capacity,

and surface wave excitation. Recently, metamaterials and EBG structures have been suggested to overcome the microstrip antenna limitations [9] and [53]. For example; the antennas miniaturization with enhanced radiation patterns, SRRs is utilized for that as cited in [54] and [55]. Furthermore, etching different EBG structures from the antenna ground planes and including EBG structures were proposed in [3] and [56]. Metamaterials possess several attractive features such as printed circuit technology compatibility, the ability to introduce distinctive stopbands, and surface wave reduction [56] and [57]. However, there are some fundamental concerns, with resonant metamaterials and EBG structures; narrow bandwidth in which the desired properties occur, and losses due to the conducting inclusions [12] and [58]. Moreover, accommodating various services such as *WiMAX, WLAN, GPS*, cellular, and Bluetooth in the same antenna terminal may acquire operating the antenna at multiple frequency bands [59]. Moreover, the antenna size, weight, and cost could increase with increasing the additional features. Therefore, one of the objectives of this research is to develop new antenna designs using EBG structures to fulfill these requirements.
From the early start of the research reported in this dissertation, the author decided to utilize different techniques based on EBG structure to design antennas for various wireless communications applications. In the first approach, a novel EBG structure based on a microstrip antenna are presented. Design, simulation, analysis, fabrication, and testing of antennas combined with EBG structures to enhance the antenna gain, radiation efficiency, bandwidth, and improved the isolation between the antenna array elements. The EBG lenses positioned over conventional square patch microstrip antennas for gain enhancement is developed. The microstrip antenna performance with and without the proposed EBG structure is compared to identify the gain enhancement. A significant enhancement is found for the antenna bore-sight gain, aperture efficiency, and the *front-to-back ratio (F/B)*. A printed monopole antenna is presented based on rectangular shaped EBG unit cells and a partial ground plane. The proposed antenna exhibits a moderate gain and orient the antenna radiation, primarily to the end-fire directions. Next, a rectangular-shaped EBG structure is utilized to a printed rectangular slot microstrip antenna array. The proposed EBG structure is placed between the radiating antenna elements to reduce the proposed antenna array mutual coupling for MIMO applications. A significant enhancement in the edge to the edge separation distance between the radiating antenna elements, *Envelope Correlation Coefficient (ECC)*, is investigated after introducing the EBG structure. The proposed antenna array mitigates the performance enhancements even after folding on a cylindrical substrate for wearable applications.

Due to the rapid developments in present wireless communication and information technologies, several approaches were developed based on DAM process as alternatives to the classical modulation approaches [29]. Therefore, in the second part of this dissertation, integrating microstrip antennas with high-speed semiconductors while maintaining the size miniaturization and keeping high gain-bandwidth produce

over the frequency band of interest is developed. In the first part of this section, the research is focused on the design, simulation, analysis, fabrication, and testing of a simple planar and folded antenna profile for DAM based on spread spectrum technology. The proposed antenna is mounted on a planar and a flexible substrate for wearable applications. Its design consists of two patches with the same geometry for DPSK modulation. The two antenna branches are delayed by a phase shift of 180° at different frequencies. The phase shift is controlled based on two PIN diodes. The proposed antenna performance on the human body based on planar, bent, and folded profiles is investigated. The proposed antenna is examined based on human tissue under three scenarios with four layers: skin, fat, muscle, and bone tissues. The biological effects from exposure to electromagnetic radiation of the human body for the proposed antenna are investigated for biomedical applications. The field strength from the proposed antenna array is measured at different human body locations with different scenarios using a $3D$ axis field strength meter. An EBG-based DPSK modulation antenna is utilized for gain enhancement.
Finally, the author designed a novel UWB monopole antenna based on re-configurable band-notch characteristics to control the desired operating bands using three PIN diodes. The reconfigurability of the frequency is accomplished by adjusting the effective electrical length of the antenna slot through the PIN diodes switching. The proposed antenna is found to operate with dual, triple, and UWB band according to the PIN diodes changing conditions. The proposed design is found to show a simple biasing process with an insignificant impact on the actual antenna performance. Such advantages are achieved through inserting the PIN diodes on the ground plane instead of the antenna patch. A reconfigurable monopole antenna based on EBG structure is utilized to improve the antenna gain and switching between different operating bands including triple, quadruple, and quintuple. The proposed antenna design shows a simple, compact, low-cost, light weight structure to suite the applications of *WiMAX* and *WiFi* systems.

5 New Scientific Results

My research aimed to improve the antenna performance in bandwidth, gain, radiation, and aperture efficiency to meet *WLAN* band requirements, especially for 5G applications. For this reason, I investigated a novel EBG structure-based microstrip antenna for antenna performance enhancement. The electromagnetic beams are focused and directed in the desired direction, resulting in increased directivity and boresight gain compared to a conventional antenna without an EBG structure. I investigated five different EBG structure-based microstrip antennas to examine the antenna gain and radiation enhancement after introducing the EBG array. My research work also covered many aspects of using EBG structure-based dipole antenna for gain enhancement and altered the radiation from boresight to end-fire direction. I investigated a single layer of EBG array structure-based antenna instead of multiple EBG layers; this is not well-developed in the literature. I also examined the possibilities and constraints of using such an EBG structure-based antenna for the MIMO system. After applying the EBG structure between the antenna array elements, a sufficient method was established by improving the mutual coupling of the antenna array elements. The second part of this dissertation focused on the reconfigurable antenna designs. Two types of reconfigurable antenna with and without EBG structure have been discussed which reconfigurability in frequency and phase reconfiguration. For this work, different antenna designs are considered for frequency and phase reconfiguration. Therefore, the operating frequency bands selectivity are directly controlled based on PIN diodes for frequency reconfiguration application. Then, the research is oriented toward the phase reconfiguration to obtain antennas-based DAM; which is controlled using two PIN diodes to obtained DPSK digital modulation. Therefore, the modulation process is controlled directly using two PIN diodes. This method of integrating the PIN diodes into the antenna system without affecting the antenna characteristics solves a difficult task. The obtained results can be summarized as follows.

5.1 Thesis I : NOVEL EBG STRUCTURES BASED ON MICROSTRIP ANTENNAS

The first thesis is concentrating on the Microstrip Patch Antenna (MPA) design and analysis based on a single layer of EBG structure to improve the proposed antenna's performances in terms of boresight gain, antenna radiation, and aperture efficiencies after introducing the EBG structure with the proposed antennas. The obtained results are summarized in the first thesis. The main effects occur after the EBG structure is used as a perfect lens; it focuses the emerged beams in the desired direction, resulting in increasing antenna gain and F/B ratio. The electrical parameters of the proposed antennas are validated using analytically using circuit theory, verified numerically and with measurements. It is described in Chapter 2 in the dissertation, and the associated publications are [J4] [J5] [C1] [C2] [C3] [C5].

5.1.1 Sub-thesis I

An EBG lens of a single layer is proposed and invented to improve the MPA gain. The proposed EBG lens is structured from a 5×5 planar array with unit cell of split concave conductive patches. The proposed EBG structure performance is proved analytically using circuit theory, tested numerically using *Finite Integration Technique (FIT)* formulations and measured using in anechoic chamber. A significant gain enhancement from 5.6 dBi of 11.1 dBi at 2.45 GHz and a *front-to-back ratio (F/B)* of about 22 dB achieved after introducing the EBG lens. The associated publications are [J4], [C5].

An EBG lens of a single layer is invented to improve the gain of a truncated slotted square patch antenna for *Wi-Fi* applications. The proposed EBG lens is structured from a 5×5 planar array. The individual unit cell is basically shaped like a couple of split concave conductive patches. The proposed EBG structure performance is tested numerically using *Finite Integration Technique (FIT)* formulations of *Computer Simulation Technology Microwave Studio (CSTMWS)* and analytically using circuit theory. The antenna performance in terms of *reflection coefficient* (S_{11}), the boresight gain, and radiation patterns are reported and compared to the performance before introducing the EBG lens to identify the significant enhancements. The proposed EBG array-based antenna is fabricated, measured, and tested using *Vector Network Analyzer (VNA)* and an anechoic chamber. A significant gain enhancement from 5.6 *dBi* of 11.1 *dBi* at 2.45 *GHz* and a F/B ratio of about 22 *dB* due to focusing the emerged beams from 99° to 26.6° are achieved after introducing the EBG lens. An excellent agreement was obtained between the simulated and measured results.

5.1.2 Sub-thesis II

A single layer of EBG structure of a 5×5 planar array is invented and located above the radiating antenna patch to enhance the gain, bandwidth, aperture efficiency, and *Half Power Beam Width (HPBW)* is presented in this part of the thesis. The proposed antenna and EBG unit cell is designed to operate at 2.45 *GHz* for *WLAN* applications. An improvement in antenna gain from 6.3 *dBi* to 13.4 *dBi* was obtained after introducing the EBG structure with the MPA. Another achievement was improving the aperture efficiency from 8.7% to 45.1% and increasing the bandwidth by 18 MHz and enhanced the *HPBW* from 77.1° to 42.1° and 118.9° to 35.8° along the *elevation* (θ) and *azimuth* (ϕ) directions, respectively. The proposed EBG array-based antenna is fabricated, measured, and tested using VNA and an anechoic chamber. The associated publications are [C1].

A single layer of EBG structure of a 5×5 planar array located above the radiating antenna patch of MPA with 70 *mm* for gain enhancement is presented in this part of thesis. The proposed antenna based on the EBG structure is operating at 2.45 *GHz* for *WLAN* applications. Parametric studies for the antenna design parameters with and without EBG planar array structure are investigated to obtain the optimal antenna performance at 2.45 *GHz*. The optimal antenna design based on the EBG array is fabricated on FR-4 substrate with maximum dimensions of $2.13\lambda_\circ \times 2.13\lambda_\circ \times 0.013\lambda_\circ$ mm^3, where $\lambda_\circ$ is the free space wavelength at 2.45 *GHz*. An improvement in antenna gain was obtained from 6.3 *dBi* to 13.4*dBi* due to emerging the radiation beams towered the desired direction. Another achievement after adding the EBG structure was improving the aperture efficiency from 8.7% to 45.1% and increased the bandwidth by 18 MHz and enhanced the *Half Power Beam Width (HPBW)* from

77.1° to 42.1° and 118.9° to 35.8° along the *elevation (θ)* and *azimuth (ϕ)* directions, respectively. The proposed EBG array-based antenna is fabricated, measured, and tested using VNA and an anechoic chamber. An excellent agreement was obtained between the simulated and measured results. Table 1 shows the proposed antenna performance with and without the EBG array. The associated publications are [C1].

Table 1: Antenna performance before and after EBG array structure.

Parameters	Without EBG	With EBG
Frequency (GHz)	2.37	2.47
$\|S_{11}\|$ (dB)	-18	-54
Bandwidth (MHz)	32	50
Realized gain (dBi)	6.3	13.4
AE %	8.7	45.1
HPBW (E_Θ)	77.1^o	42.1^o
HPBW (H_ϕ)	118.9^o	35.8^o

5.1.3 Sub-thesis III

This section presented a 3×3 EBG array mounted on top of a truncated slotted square patch antenna for gain and radiation and aperture efficiency enhancements. The SRR geometry inspires the proposed EBG unit cell. Equivalently, a circuit model is derived to compute the S-parameters of the EBG array and compared against those obtained from the numerical simulations. Later, the S_{11} spectra, gain, aperture efficiency, and radiation patterns of the EBG-based antenna are examined numerically and experimentally. After introducing the EBG array, the gain increased significantly, from 3.4 dBi to 8.95 dBi at 5.2 GHz. The proposed antenna bandwidth covers frequencies 5.15 GHz to 5.8 GHz and provides a 31% increase in aperture efficiency. *HPBW* is reduced from 107.27 ° to 86.6 ° in the E-plane and 124.37 ° to 66.8 °in the H-plane, respectively. The proposed EBG array-based antenna is fabricated, measured, and tested using a VNA and an anechoic chamber. An excellent agreement was obtained between the simulated and measured results. The associated publications are [J5].

A 3×3 EBG array mounted on top of a truncated slotted square patch antenna for gain and radiation and aperture efficiency enhancements were presented in this part. The proposed EBG unit cell is inspired from the SRR geometry. The proposed EBG array is located at approximately $0.7\lambda_\circ$, where $\lambda_\circ$ is the free space wavelength at 5.2 GHz, from the antenna patch. Equivalently, a circuit model is derived to compute the S-parameters of the EBG array and compared against those obtained from the numerical simulations. Later, the performance of the EBG based antenna is investigated numerically and experimentally in terms of S_{11} spectra, gain, aperture efficiency, and radiation patterns. The EBG array and antenna dimensions are investigated to maximize the boresight gain at 5.2 GHz for *WiMAX* applications. On an FR-4 substrate with maximum dimensions of $70 \times 70 \times 1.6$ mm^3, the optimal antenna design is fabricated. A significant gain enhancement is achieved, from 3.4 dBi to 8.95 dBi at 5.2 GHz, after introduced the EBG array. The proposed antenna bandwidth covers the frequencies from 5.15 GHz to 5.83 GHz with an excellent improvement in the aperture efficiency of about 31%. A significant $HPBW$ reduction at E-plane and H-plane from 107.27° to 86.6° and from 124.37° to 66.8°, respectively, is achieved. The proposed EBG array-based antenna is fabricated, measured, and tested using VNA and an anechoic chamber. An excellent agreement was obtained between the simulated and measured results. Table 2 shows the proposed antenna performance with and without the EBG array. The associated publications are [J5].

Table 2: The antenna performance with/without EBG array structure

Parameters	Without EBG	With EBG
Frequency (GHz)	5.2	5.21
S_{11} (dB)	-42	-23
B.W (MHz)	188	244
Gain (dBi)	3.4	8.95
AE %	12	43

5.2 Thesis II : MONOPOLE ANTENNA BASED ON EBG ARRAY FOR NOVEL APPLICATIONS

A moderate gain monopole antenna for *GSM* and *Wi-Max* applications is presented in this thesis. A monopole antenna based on an EBG structure is designed, fabricated, and tested to improve the antenna gain and radiation. The proposed antenna based on an EBG structure is printed on Roger substrate of 3006 families with resonance at 1.85 and 3.3 *GHz*. The proposed EBG layer is introduced with the antenna structure to enhance the antenna gain and orient the antenna radiation, mainly from boresight to the end-fire direction. Before the fabrication, the optimal antenna performance is validated numerically based on two different simulations, *CSTMWS* and *HFSS*. At 1.85 *GHz* and 3.3 *GHz*, the antenna exhibits end-fire radiation patterns with gains of 2.88 *dBi* and 5.8 *dBi*, respectively. The gain enhancement is due to the EBG array, which matches the antenna aperture impedance to the free space impedance. The antenna is fabricated and tested experimentally to validate the obtained numerical results in terms of S_{11} and radiation patterns at 1.85 *GHz* and 3.3 *GHz*. The measured results show a good agreement with the simulated one. The simulated and measured results show that adopting the EBG structure improves the proposed antenna performance. The publication associated with Thesis 2 is [J2].

The second thesis deals with a monopole antenna design constructed from a traditional monopole antenna printed on Roger substrate of 3006 family with resonance at 1.85 and 3.3 *GHz*, respectively, based on an EBG structure to enhance the antenna performance. An EBG layer is introduced to the antenna structure to enhance the antenna gain and orient the antenna radiation, mainly from boresight to the end-fire direction. A moderate gain monopole antenna is proposed for *Global System for Mobile Communications (GSM)* and *Wi-Max* applications. Several parametric studies based on numerical simulations of CSTMWS formulations are conducted to realize the optimal antenna design. The optimal antenna performance is validated numerically with *Finite Element Method (FEM)* based on *High Frequency Structure Simulator(HFSS)* before the fabrication. It is found that the antenna shows end-fire radiation patterns with a gain of 2.88 *dBi* and 5.8 *dBi* at 1.85 *GHz* and 3.3 *GHz*, respectively. The achieved gain enhancement is due to introducing the EBG array, which matches the antenna aperture impedance to the free space impedance. The antenna is fabricated and tested experimentally to validate the obtained numerical results in terms of S_{11} and radiation patterns at 1.85 *GHz* and 3.3 *GHz*. The measured results show a good agreement with the simulated results. Finally, Table 3 summarizes the antenna performance in terms of S_{11}, boresight gain, bandwidth, and radiation efficiency with and without EBG structure. It is found that the proposed antenna performance is improved after introducing the EBG structure. This part is described in detail in

Chapter 3 of the dissertation. The publication associated with Thesis 2 is [J2].

Table 3: The proposed antenna performance with and without EBG structure.

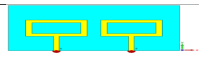
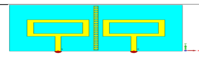
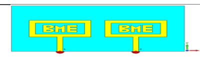
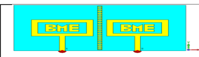
Parameters	Without EBG	Without EBG	With EBG	With EBG
	f_1	f_2	f_1	f_2
Frequency (GHz)	1.85	3.3	1.85	3.3
S_{11} (dB)	-26.1	-27.1	-21	-29
Bandwidth (MHz)	178	288	221	201
Boresight gain (dBi)	1.11	2.25	2.88	5.8
Radiation efficiency %	34	20.9	53.6	78

5.3 Thesis III : EBG DEFECTS FOR MUTUAL COUPLING REDUCTION IN MIMO SYSTEMS

This thesis proposes a novel EBG structure between two planar monopole antenna elements to improve the mutual coupling for *MIMO* applications. The proposed antenna array consists of two slotted rectangular patch antennas mounted on the low-cost FR-4 substrate. Two prototype planar monopole antennas with and without the BME Logo configuration are fabricated, measured, tested, and validated in scattering parameters, bandwidth, radiation patterns, and boresight gain. The antenna array structure is folded on a cylindrical substrate for wearable applications. For the proposed antenna design, the simulated and measured results are agreed with each other. By introducing the EBG structure within the antenna array, a significant reduction in the mutual coupling between the array elements below -29 dB and -25 dB for the first geometry at 2.5 GHz and 5.8 GHz, respectively. And for the second antenna array geometry based on *BME Logo*, the mutual coupling is reduced below -39 dB and -23 dB at 2.5 GHz and 5.8 GHz, respectively. This improvement in mutual coupling is due to the suppression of the surface waves between patches elements. An improvement in MIMO antenna system has been obtained in terms of ECC, DG, $TARC$, MEG, and CCL after introducing the EBG structure with the proposed antenna. It is found ECC less than 0.0005, the value of DG touching 10 dB, $TARC$ less than 0.25, MEG value is touching 0 dB, and CCL less than 0.2 ($bits/sec/Hz$) for the two operating frequency bands after introducing the EBG structure. Unlike other mutual coupling reduction methods, the proposed antenna design increased the antenna gain by 0.4 dB and 0.5 dB at 2.5 GHz and 5.8 GHz, respectively. Therefore, the proposed antenna is suitable for modern wearable and portable wireless communication systems. The publication associated with Thesis 3 is [J3], [J7].

In this thesis, a novel EBG structure is proposed between two planar monopole antenna elements to improve the mutual coupling for the *MIMO* applications. A parametric study investigates the antenna array performance to utilize the optimal dimensions that satisfy *WLAN* and *Wi-Fi* applications requirements. The proposed antenna array consisting of two slotted rectangular patch antennas built on the low-cost FR-4 substrate. Two prototypes planar monopole antennas with and without the *BME Logo* configuration are fabricated, measured, tested, and validated in scattering parameters, bandwidth, radiation patterns, and boresight gain. The separation distance between the proposed antenna elements is found about $\lambda_o/16$, where $\lambda\circ$ is the free space wavelength at 2.5 GHz with low mutual coupling. The antenna array structure is folded on a cylindrical substrate for wearable application. The simulated and measured results for the proposed antenna design are agreed with each other. It is concluded that by introducing the EBG structure within the antenna array, a significant reduction in the mutual coupling between the array elements below -29 dB and -25 dB for the first geometry at 2.5 GHz and 5.8 GHz, respectively. While the mutual coupling is reduced below -39 dB and -23 dB at 2.5 GHz and 5.8 GHz, respectively, for the second antenna array geometry based on *BME Logo*. Another achievement has been obtained after introducing the EBG structure, the *MIMO* antenna performance improved in terms of *Envelope Correlation Coefficient (ECC)*, *Diversity Gain (DG)*, *Total Active Reflection Coefficient (TARC)*, *Mean Effective Gain Difference (MEG)*, and *Channel Capacity Loss (CCL)*. A reduction in *ECC* to about 0.0005, *DG* is close to 10 db, *TARC* less than 0.25, *MEG* value is touching 0 dB, and *CCL* is less than 0.2 ($bits/sec/Hz$) are achieved after introducing the EBG structure for the two operating frequency bands. Therefore, such isolation is motivated the author to apply the proposed antenna design for *MIMO* applications. Unlike other mutual coupling reduction methods, the proposed antenna design increased the antenna gain by 0.4 dB and 0.5 dB at 2.5 GHz and 5.8 GHz, respectively, in addition to the mutual coupling reduction within a separation distance of $0.06\lambda_\circ$. The resonant frequency, S_{11}, gain, and *ECC* numerical values from the proposed array structures are compared to each other and listed in Table 4. It is found that the proposed antenna performance is improved after introducing the EBG structure due to suppression of the surface waves between patches. Finally, the proposed *MIMO* antenna is found a good candidate for modern wearable and portable wireless communication systems. This part is described in detail in Chapter 4 of the dissertation. The publication associated with Thesis III is [J3], [J7].

Table 4: The antenna performances before and after introducing the EBG structure

Structure				
S (mm)	7.6	7.6	7.6	7.6
f_o (GHz)	2.45, 5.8	2.45, 5.8	2.5,5.7	2.5,5.8
$\|S_{11}\|$ (dB)	-25, -20	-15, -18	-15, -40	-12, -14
$\|S_{21}\|$ (dB)	-6, -10	-29, -25	-7, -12	-39, -23
Gain (dB)	1.8, 2.7	2.1, 3.1	1.2, 1.9	1.7, 2.4
ECC	0.001,0.01	0.0005,0.0006	0.01,0.001	0.008,0.0003

5.4 Thesis IV : DESIGN OF A CONTROLLABLE ANTENNA BASED ON EMBEDDED DIFFERENTIAL PSK MODULATION

The fourth thesis presents a simple planar and folded antenna profile for *Direct Antenna Modulation(DAM)* based on spread spectrum technology. In this design, I explored the modulation process of electromagnetic signals in the antenna circuit design directly. To perform the *Differential Phase Shift Keying (DPSK)* modulation, two identical antennas are fed by a two-branch microstrip line with a phase shift 180°. The phase shift of the RF signals is controlled based on two PIN diodes through a transmission line network located between antenna elements. The proposed antenna performance on the human body based on planar, bent, and folded profiles is investigated. The proposed antenna is examined based on human tissue under three scenarios with four layers: skin, fat, muscle, and bone tissues. The biological effects from exposure to electromagnetic radiation of the human body are investigated in this thesis also. The field strength from the proposed antenna array is measured at different human body locations with different scenarios using a $3D$ axis field strength meter. A single layer of EBG structure of a 3×3 SRR unit cells planar array is invented and located in close to the proposed *DPSK* antenna for gain enhancement. The proposed antenna achieved peak realized gain of 4.15 and 4.73 dBi at 5 GHz for two PIN diode states without EBG structure ; however, with the integration of EBG with the proposed antenna, the antenna gain increased to 7.5 and 8.6 dBi, respectively. The publication associated with Thesis IV is [J1],[C4].

In this thesis work, I presents a simple planar and folded antenna profile for *DAM* based on spread spectrum technology. In this design, I explored the modulation process of electromagnetic signals in the antenna circuit design directly. To perform the *DPSK* modulation, two identical antennas are fed by a two-branch microstrip line with a phase shift of 180° at different frequencies. The patch structure is fed with a 50 Ω microstrip line network of two branches and delayed by a phase shift of 180°. The phase shift of the RF signals is controlled based on two PIN diodes through a transmission line network located between antenna elements. The antenna performance based on the planar and folded profile in terms of S_{11} and phase difference spectra are presented in Table 5. The proposed antenna performance on the human body based on planar, bent, and folded profiles is investigated see Table 6. The proposed antenna is examined based on human tissue under three scenarios with four layers: skin, fat, muscle, and bone tissues. Since the proposed antenna is designed for biomedical applications, the biological effects from exposure to electromagnetic radiation of the human body are investigated in this thesis as indicated in Table 7. The field strength from the proposed antenna array is measured at different human body locations with different scenarios using a $3D$ axis field strength meter. The other significant aspect of this research is reducing the patch size to be suitable for wearable devices. Therefore, a cylindrical substrate is utilized for bending the proposed antenna structure. The proposed antenna design shows a gain of 4.73 dBi and 2.5 dBi for the planar and folded antenna profile, respectively. The proposed antenna based on an EBG array is introduced to enhance the antenna gain. The proposed antenna achieved peak realized gain of 4.15 and 4.73 dBi at 5 GHz for two PIN diode states without EBG structure ; however, with the integration of EBG with the proposed antenna, the antenna gain increased to 7.5 and 8.6 dBi, respectively. The performance of the proposed antenna with and without the EBG array is shown in Table 8. The obtained results indicated that the antenna performance in terms of S_{11} spectra and the realized gain had been improved after introducing the EBG structure with the proposed antenna array. In comparison between the proposed work with related work published in the literature, my proposed work has novelty: simplicity of controlling the switching mechanism, high gain, low profile, simple, easy to fabricate, easy to control the phase-shifting and activation of the antenna, and easy to integrate with other devices. Finally, an excellent agreement is found between the obtained numerical results and measurements. The publication associated with Thesis IV is [J1], [C4].

Table 5: Comparison between planar and folded antenna performance.

Antenna profile	Frequency (GHz)	$\|S_{11}\|(dBi)$	Bandwidth (MHz)	Gain (dB)	Phase
Planar ($SW1-ON$)	5	-10.55	334	4.15	173.2°
Planar ($SW2-ON$)	5	-12.6	1190	4.73	-7.4°
Folded ($SW1-ON$)	5.03	-55	752	2.45	-111.6°
Folded ($SW2-ON$)	5.03	-62	646	2.50	61.7°

Table 6: The proposed antenna performance based on planar, bent, and folded profile.

Antenna Type	Frequency (GHz)	S_{11} (dB)	Gain (dBi)	Bandwidth (MHz)	Phase shift (degree)
Planar ($SW1-ON, SW2-OFF$)	5.15	-14	4.15	612	173.2°
Planar ($SW1-OFF, SW2-ON$)	4.85	-31.5	4.73	775	-7.4°
Bent ($SW1-ON, SW2-OFF$)	4.65	-14	4.7	375	132.6°
Bent ($SW1-OFF, SW2-ON$)	4.34	-26.5	4.82	675	-41.9°
Folded ($SW1-ON, SW2-OFF$)	4.58	-11.8	2.45	525	-111.6°
Folded ($SW1-OFF, SW2-ON$)	4.5	-21.5	2.5	1125	61.7°

Table 7: Comparison between the field strength leakage at different scenarios from the human body parts.

Location	Profile	Field strength (mV/m)	Location	Profile	Field strength (mV/m)
Arm	Planar	50	Thigh	Planar	140
Arm	Bended	45	Thigh	Bended	150
Head	Planar	199	Chest	Planar	207
Head	Bended	188	Chest	Bended	189

Table 8: Comparisons of the proposed planar antenna performance with and without EBG.

Antenna Type	Frequency (GHz)	S_{11} (dB)	Bandwidth (MHz)	Gain (dBi)
without EBG ($SW1-ON, SW2-OFF$)	5	-10.55	334	4.15
without EBG ($SW1-OFF, SW2-ON$)	5	-12.6	1190	4.73
with EBG ($SW1-ON, SW2-OFF$)	5.09	-19	992	7.5
with EBG ($SW1-OFF, SW2-ON$)	4.92	-29.1	754	8.6

5.5 Thesis V : A NOVEL UWB MONOPOLE ANTENNA WITH RECONFIGURABLE BAND NOTCH CHARACTERISTICS BASED ON PIN DIODES

In this thesis, two types of reconfigurable antenna with and without EBG structure have been discussed which reconfigurability in frequency and bandwidth parameters. A frequency reconfigurable *ultra-wideband (UWB)* monopole antenna was developed numerically and experimentally. The proposed antenna is compact, low cost, lightweight, and easy to control bandwidth and frequency *UWB* reconfigurable antenna based on PIN diodes. The proposed antenna is comprised of a modified circular patch and a partial ground plane. The proposed antenna covers the entire *UWB* spectrum from 1.7 *GHz* to 11 *GHz*. The reconfigurability of the frequency is accomplished by adjusting the effective electrical length of the proposed slot antenna. The reconfigurability is based on three PIN diodes inserted within a slotted ground plane. The frequency reconfigurability is employed based on the eight PIN diode states with UWB, dual, and triple operating bands, which can be obtained by changing the PIN state from *ON-OFF* and vice versa. The research is extended to introduce the EBG structure to improve the proposed antenna's bandwidth, directivity, and realized gain. An EBG array consisting of 3×3 circular SRR unit cells is designed and placed in close to the proposed monopole antenna for antenna gain enhancement and frequency reconfigurability. To provide the desired antenna qualities of frequency reconfigurability, high gain, and directivity, the proposed antenna based on the EBG structure has been developed. The reconfigurability of the frequency based on EBG structure is accomplished by integrating two PIN diodes placed within each inner and outer SRR unit cells. By adjusting the EBG-based PIN diodes, triple, quadruple, and quintuple operating bands can be obtained by changing the PIN diodes from *ON-OFF* and vice-versa. The final proposed antenna prototype is compact, as well as it enhances antenna gain for all operating bands by five *dBi*. The proposed antenna is fabricated, measured, and tested using VNA and an anechoic chamber. The associated publications are [J6].

The fifth thesis presents two types of reconfigurable antenna with and without EBG structure. The proposed antennas are compact, high gain, low cost, lightweight, easy to control bandwidth and frequency notch *UWB* reconfigurable antenna based on PIN diodes. The proposed antenna is comprised of a modified circular patch and a partial ground plane. The proposed antenna is designed to cover the entire*UWB* spectrum from 1.7 *GHz* to 11 *GHz*. The first reconfigurable antenna system based on the insertion of three PIN diodes placed within a slotted ground plane. The frequecny reconfigurable is achieved by switching three PIN diodes *ON-OFF* states. The reconfigurability is accomplished by adjusting the effective electrical length of the proposed slot antenna which is employed based on the eight PIN diode states with UWB, dual, and triple operating bands, which can be obtained by changing the PIN state from *ON-OFF* and vice versa.

Due to the biasing circuit's simplicity, ease of selecting the position to connect the biasing circuit, little impact on antenna bandwidth, gain, and radiation efficiency, the proposed PIN diodes as a switching device are mounted within the ground plane instead of the antenna patch body. The main reason to choose three PIN diodes as switches is to change the proposed antenna's effective electrical length to achieve the frequency reconfigurability. A UWB, dual, and triple operating bands can be obtained by altering the PIN diode state switches between forward and reverse conditions. When all the switches are in the *OFF* state, the proposed antenna performed is in a UWB operation band (1.85-10.9) *GHz*. The proposed antenna operates in dual-band mode (2.7-3.5) *GHz* and (5.4-6.46) *GHz* when all switches are in the *ON* state. The other six diode conditions, the operating band 2.7-3.5, 5.4-6.4, 7.5-8.4, and 8.87-10.05 *GHz*, are achieved. Therefore, a systematic parametric study based on numerical analysis is invoked to refine the proposed performance. The proposed antenna is fabricated on FR-4 substrate with dimensions of $50 \times 60 \times 1 mm^3$ and connected to a bias tee circuit through the SMA port of 50 Ω input impedance. The PIN diodes are connected to the DC source, power supply, through the positive negative electrodes that come out from the bias tee to ensure no interference between the DC and the RF sources. The proposed antenna performance is tested experimentally and compared to the simulated results from a commercial software package based on *CSTMW* with a *FIT* algorithm. The experimental results are found to agree very well with simulated results. Next, a frequency reconfigurable monopole antenna based on EBG structure was designed and developed numerically. An EBG structure consists of circular 3×3 SRR unit cells invoked and placed in close to the proposed monopole antenna to improve the antenna's performance in terms of bandwidth and realized gain. The EBG structure is utilized with the proposed antenna to provide the desired antenna qualities of frequency reconfigurability, high gain, and directivity. The final proposed antenna prototype is compact, as well as it enhances antenna gain for all operating bands by almost 5 *dBi*. It is found that the proposed antenna design is simple geometry and easy to control the frequency bands to suit the applications of *WiMAX* and *WiFi* systems. Finally, the proposed antenna could serve as a practical multimode application such as *UWB* and military reconfigurable frequency antennas. The publication associated with Thesis V is [J6].

6 Summary of the Research Results and Conclusions

In this dissertation, my first contribution group covers the design of several antennas based on EBG structures for enhancing the antenna performance in terms of gain and radiation, and aperture efficiency. Several EBG structures are utilized to develop the microstrip antenna and address highly directive microstrip antennas, broad-band, and end-fire radiation for wireless and wearable applications. An EBG structure consisting of a single layer is developed to enhance the gain of the proposed microstrip antennas. The EBG lens demonstrates a remarkable improvement in the boresight gain and radiation and aperture efficiency. Next, my second contribution group focused on using a novel EBG structure based on two planar monopole antennas to improve the antenna mutual coupling for the MIMO applications. The second part of this dissertation focused on the reconfigurable antenna designs. Two types of reconfigurable antenna with and without EBG structure have been discussed which reconfigurability in frequency and phase reconfiguration. For this work, different antenna designs are considered for frequency and phase reconfiguration. Therefore, the operating frequency bands selectivity are directly controlled based on PIN diodes for frequency reconfiguration application. Then, the research is oriented toward the phase reconfiguration to obtain antennas-based DAM; which is controlled using two PIN diodes to obtained DPSK digital modulation. Therefore, the modulation process is controlled directly using two PIN diodes. The new results can be summarized as follows.

1- My first group of contributions deals with an improvement of the MPA performances, which can be obtained in terms of antenna gain, antenna radiation, and aperture efficiencies after introducing the EBG structure-based antennas.

1-1 I designed, fabricated, and tested a circular truncated slotted square patch antenna based on a novel EBG array of 5×5 unit cells for gain enhancement. A remarkable improvement in the bore-sight gain, from 5.6 dBi up to 11.1 dBi at 2.45 GHz with an F/B exceeds the 22 dB have been obtained after introducing the EBG array [C5][J4].

1-2 I presented an array of 5×5 slotted EBG structure based on the conventional MPA for gain and aperture efficiency enhancement. Single-layer of EBG structure located above the radiating antenna patch. An improvement in the antenna gain from 6.3 dBi to 13.4 dBi at 2.45 GHz and apperture efficiency from 8.7% to 45.1% have been obtained after introducing the EBG array [C1].

1-3 I introduced a uniform planar array of 3×3 EBG layer placed on top of an MPA for bandwidth, radiation patterns, boresight gain, and aperture efficiency enhancement. The proposed MPA and EBG unit cells are designed to be operating at 5.2 GHz for WiMAX applications. The antenna performance is enhanced in terms of realized gain from 3.4dBi to 8.95dBi, and from 188 MHz to 244 MHz in terms of bandwidth, and in terms of the aperture efficiency from 12% to 43% after adding the EBG structure with the proposed antenna [J5].

1-4 I designed a single layer of 3×3 EBG array placed on a conventional square patch microstrip antenna for gain and radiation efficiency enhancement. The EBG unit cell is inspired from asterisk shape and structured as square geometry with 8 pins. The proposed EBG unit cells and antenna are designed to operate at 5.8 GHz for WLAN applications. An improvement in the antenna gain from 1.5dBi up to 11.2dBi at 5.8GHz with aperture efficiency from 4.1% to 38.8% have been achieved after introducing the EBG array [C3].

1-5 I demonstrated of the feasibility of using the EBG structure based MPA for gain and aperture efficiency enhancement. To improve the proposed antenna gain, a 3×3 array based on EBG is implemented as a single planar array to covers the radiating patch antenna. The proposed antenna and EBG unit cell are designed to operate at 5.8 GHz to match the WLAN and WiMAX applications. The antenna based on EBG structure is provided boresight gain enhancement from 1.8 dBi to 11.4 dBi. Another achievements have been obtained after introducing the EBG array by enhancing the aperture efficiency from 3.2% to 29.6% and increased the bandwidth by 85 MHz and improving the HPBW from 112° to 34° and 136° to 66° along the elevation and azimuth directions, respectively [C2].

The simulated results have been compared with measured results and proved that the proposed antenna design-based EBG structure is better than the published results found in the literature.

2- In my second contribution group, I introduced new contributions regarding using EBG structure based on printed monopole antenna to enhance the antenna gain and orient the antenna radiation, mostly from the boresight to end-fire directions. It is found that the antenna shows end-fire radiation patterns with a gain of 2.88 dBi and 5.8 dBi at 1.85 GHz and 3.3 GHz, respectively, after introducing the EBG structure. The measured results of the proposed antenna design show good agreement with the simulated results. The proposed antenna design is suiting the applications of *GSM* and *Wi-Max* bands in portable wireless systems [J2].

3- In the third contribution group, I elaborated a technique for mutual coupling reduction based on using the EBG structure. For this, I designed a low-profile and closely spaced two-element antenna for the MIMO application. The antenna is designed based on the combination of novel slotted EBG structures to reduce the mutual coupling between antenna elements.

3-1 For the first antenna design, I designed, fabricated, and tested an array of slotted antenna elements based on EBG structure. The EBG structure positioned between two planar monopole slot patch antennas to enhance the mutual coupling of the MIMO system. An isolation improvement is achieved from -6 dB to -29 dB for the first operating band (2.5 GHz) and from -10 dB to -25 dB for the second operating band (5.8 GHz) after introducing the EBG structure. An improvement in MIMO antenna system has been obtained in terms of ECC, DG, $TARC$, MEG, and CCL after introducing the EBG structure with the proposed antenna array. It is found that ECC

is less than 0.0005, DG close to 10 dB, $TARC$ less than 0.25, MEG is touching 0 dB, and CCL is less than 0.2 ($bits/sec/Hz$) for the two operating bands [J3].

3-2 Using the EBG structure positioned between the monopole antenna elements, I demonstrated the applicability of improving the mutual coupling for the proposed antenna based on the BME Logo. An isolation improvement is achieved from -7 dB to -39 dB for the first operating band (2.5 GHz) and from -12 dB to -23 dB for the second operating band (5.8 GHz) after introducing the EBG structure. An improvement in MIMO antenna system has been obtained in terms of ECC, DG, $TARC$, MEG, and CCL after introducing the EBG structure with the proposed antenna array. It is found that ECC is less than 0.0008, DG close to 10dB, $TARC$ less than 0.25, MEG is touching 0 dB, and CCL is less than 0.2 ($bits/sec/Hz$) for the two operating bands [J7].

Unlike other mutual coupling reduction methods, the proposed antenna design increases the antenna gain by 0.4 dB and 0.5 dB at 2.5 GHz and 5.8 GHz, respectively, in addition, reducing the separation distance of $0.06\lambda_\circ$ between the antenna array elements.

4-In the second part of this dissertation, I proposed new techniques for *DAM*. For this, I designed, implemented, and experimental evaluation of the direct antenna *Differential PSK* digital modulation. The proposed antenna design consists of two branches and delayed by a phase shift of 180° at different frequencies. Via controlling the PIN diodes state, the phase shift of the proposed reconfigurable antenna can be controlled directly by changing the PIN diodes within two statuses: ON and OFF. In the developed prototype, the two antenna branches wave phase is directly changing according to the baseband control signal based on (ON-OFF) diodes states. The proposed antenna is examined based on human tissue under three scenarios with four layers: skin, fat, muscle, and bone tissues. The biological effects from exposure to electromagnetic radiation of the human body were investigated using a 3D axis field strength meter. The proposed antenna-based PIN diodes are fabricated to realize and test the *DPSK* modulation process experimentally. The proposed antenna invoked EBG structure consists of square SRR unit cells to improve the antenna gain. The obtained results indicate that the EBG structure enhanced the antenna performance by increasing the antenna gain and bandwidth. The proposed antenna achieved a peak realized gain of 4.15 and 4.73 dBi without EBG; however, by integration the EBG structure with the proposed antenna, the antenna gain increased to 7.5 and 8.6 dBi, respectively. The obtained results measurements show good agreements with the proposed model and *CSTMWS* simulations. Therefore, the proposed antenna design is a good candidate for multiple wireless communications systems such as wearable applications [J1][C4].

5-The last group of contributions focuses on the new strategy based on novel reconfigurable based on PIN diodes to control the bandwidth and achieve notched

UWB band characteristics. Two types of reconfigurable antenna with and without EBG structure have been discussed which reconfigurability in frequency and bandwidth parameters. The first reconfigurable antenna system is achieved by switching three PIN diodes *ON-OFF* states. The frequency reconfiguration is accomplished by adjusting the effective electrical length of the proposed slot antenna. An UWB, dual, and triple operating bands can be obtained by altering the PIN diode state switches between forward and reverse conditions. When all the switches are *OFF* state, the proposed antenna performed is in a UWB operation band (1.85-10.9) *GHz*. The proposed antenna operates in dual-band mode (2.7-3.5) *GHz* and (5.4-6.46) *GHz* when all switches are *ON* state. The other six diode conditions, the operating band 2.7-3.5, 5.4-6.4, 7.5-8.4, and 8.87-10.05 *GHz*, are achieved. Next, a frequency reconfigurable monopole antenna based on EBG structure was designed and developed numerically. An EBG structure consists of circular SRR unit cells invoked and placed in close to the proposed monopole antenna to improve the antenna's performance in terms of bandwidth and realized gain. The EBG structure is utilized with the proposed antenna to provide the desired antenna qualities of frequency reconfigurability, high gain, and directivity. The proposed frequency reconfigurable antenna based on EBG was utilized to obtain triple, quadruple, quintuple operating bands with improvement in antenna gain about 5 *dBi* at all the operating frequency bands. Therefore, the proposed antenna could serve as an effective multimode application such as *UWB* and military reconfigurable frequency antennas. [J6].

7 Recommendation for future research

Based on the obtained findings from the current work, the following recommendations and feature aspects are suggested:

1-Beam splitting based on reconfigurable novel EBG structure of microstrip antenna. In this dissertation, the microstrip antenna based on the EBG lens is used to enhances and implements high microstrip antenna gain. The proposed EBG lens-based antenna can split the radiation pattern into beams that are usual for radar applications. In this work, the reconfigurable antenna can be developed using the beam splitting process, using an EBG structure instead of the conventional beam splitting technique.

2-In this work, a moderate gain monopole antenna was designed to suit the *GSM* and *Wi-Max* applications. An EBG layer was ultimately introduced to the antenna structure to enhance the antenna performance and oriented the antenna radiation to the end-fire directions. Therefore, the antenna can be designed to demonstrate a remotely controlled, reconfigurable performance by modifying the light intensity on an array of photo-resistors integrated with the EBG array.

3-The designed *UWB* antenna provides only the frequency reconfigurable characteristics. Therefore, the proposed antenna could be further extended to develop and evaluate the designed *UWB* circuit antenna based on artificial material for RF Energy harvesting for *IoT* applications and *WSNs*.

4-The designed *UWB* antenna is only included the frequency reconfigurable features. Based on different tuning methodologies, such as frequency bands, polarization, and radiation patterns, the reconfigurable antenna may also be utilized for modern wireless devices..

5-For *DAM* this study examined the modulation of electromagnetic signals in the antenna circuitry design directly on planar and cylindrical antennas to perform a *DPSK* modulation for wearable applications. Therefore, the proposed antenna could explore the modulation process for *ASK* and *QPSK* modulation of electromagnetic signals.

8 Publications

Individual submission table:

No.	Itemized publication requirements	Own Number of publications	<>	required minimum	Has it been fulfilled (Yes/No)
1	Minimum number of publications: 4	27	>	4	-
2	At least 2 articles were published in a peer-reviewed journal in a foreign language	11	>	2	-
3	Of which at least 1 article published in a journal in the Web of Science or Scopus database	8	>	1	-
4	Number of peer - reviewed publications at least 2	11	>	2	-
5	At least 2 publications in a foreign language, with at least 50% of the candidate	17	>	2	-
6	Publication score at least 12	64.7	>	12	-
7	Number of independent citations (5 January 2022):	239	-	-	-

Publications linked to the theses:

Thesis	Journal papers	International conference
Thesis 1	[J4], [J5]	[C1],[C2],[C3],[C5]
Thesis 2	[J2]	-
Thesis 3	[J3],[J7]	-
Thesis 4	[J1]	[C4]
Thesis 5	[J6]	-

8.1 International Journals and conferences (Peer-reviewed)

- International Journals

[J1] **Yahiea Alnaiemy**, and Lajos Nagy. "Design of a Controllable Antenna Based on Embedded Differential PSK Modulation." *Progress In Electromagnetics Research B (PIER B)*, Vol. 90, 43-62, (**2021**). (WOS, IF=1.898, Q3), ,(Cited by 1).

[J2] **Yahiea Alnaiemy**, Taha A. Elwi, and Lajos Nagy. An end fire printed monopole antenna based on electromagnetic band gap structure. *Automatika, Journal for Control, Measurement, Electronics, Computing and Communications*, **2020**, Vol. 61, NO. 3, 482–495. (WOS, IF=0.764, Q2),,(Cited by 7).

[J3] **Yahiea Alnaiemy**, Taha A. Elwi, and Lajos Nagy. Mutual coupling reduction in patch antenna array based on EBG structure for MIMO applications. *Periodica Polytechnica Electrical Engineering and Computer Science*, Vol. 63, NO. 4, 332–342. **2019.** (Q3),(Cited by 12).

[J4] **Yahiea Alnaiemy**, Taha A. Elwi, Lajos Nagy and Thomas Zwick. A Systematic Analysis and Design of a High Gain Microstrip Antenna based on a Single EBG Layer. *INFOCOMMUNICATIONS JOURNAL*,Vol. x, NO. 4, 22–30. **2018**. (WOS,Q4),(Cited by 5).

[J5] **Yahiea Alnaiemy**, and Lajos Nagy. Radiation Performance Enhancement of a Microstrip Antenna Based on EBG at WiMAX Bands. *Journal Scientific Bulletin Series C Electrical Engineering and Computer Science*, (**2021**). (WOS, IF=0.619, Q3).

[J6] **Yahiea Alnaiemy**, and Lajos Nagy. A Novel UWB Monopole Antenna With Reconfigurable Band Notch Characteristics Based on PIN Diodes. *Infocommunications Journal*, (**2021**). (Scopus, WOS, IF=0.7, Q3).

[J7] **Yahiea Alnaiemy**, and Lajos Nagy. Mutual Coupling Suppression by EBG Structure Based Planar Monopole Antenna Array for MIMO Applications. *Transactions on Electrical and Electronic Engineering (IEEJ)*, (**2021**). (WOS, IF=0.668, Q3).

- **International Conferences**

[C1] **Yahiea Alnaiemy**, and Lajos Nagy. "Electromagnetic Band Gap Structure for Microstrip Antenna Gain Enhancement at WLAN Band." *International RF and Microwave Conference (RFM)*. IEEE, RFM2020, **2020**. (WOS, Scopus),(Cited by 1).

[C2] **Yahiea Alnaiemy**, and Lajos Nagy. "Further Investigation of The Feasibility of Using EBG Structure-Based Microstrip Antenna for Gain Enhancement." *International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET)*. IEEE, **2020**. (WOS, Scopus),(Cited by 1).

[C3] **Yahiea Alnaiemy**, and Lajos Nagy. ”Improved antenna gain and efficiency using novel EBG layer.” *2020 IEEE 15th International Conference of System of Systems Engineering (SoSE)*. IEEE, RFM2020, **2020**. (WOS, Scopus),(Cited by 4).

[C4] **Yahiea Alnaiemy**, Taha A. Elwi, and Lajos Nagy. ”A Folded Microstrip Antenna Structure Based Differential Phase Shift Keying Modulation Technique.” *18th International Symposium on Computational Intelligence and Informatics. IEEE, RFM2020*, **2018**. (WOS, Scopus)(Cited by 2).

[C5] **Yahiea Alnaiemy**, Taha A. Elwi, and Lajos Nagy. ”Enhancing the microstrip antenna gain using a novel EBG lens based on a single layer.” *2018 11th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*. IEEE, **2018**. (WOS, Scopus)(Cited by 10).

[C6] **Yahiea Alnaiemy**, and Lajos Nagy. ”Design and analysis of Ultra-Wide Band (UWB) antennas based on metamaterial. *” 2018 11th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*. IEEE, **2018**. (WOS, Scopus)(Cited by 6).

8.2 Other related own publication (Peer-reviewed)

[J8] Haider M. AlSabbagh, Taha A. Elwi, **Yahiea Alnaiemy**, and Hussain M. Al-Rizz. ”A compact triple-band metamaterial-inspired antenna for wearable applications.” *Microwave and Optical Technology Letters, Wiley*, Vol. 62, Issue 2, Pages 763-777, July (**2019**). (WOS, IF=0.957, Q2)(Cited by 16).

[C7] Taha A Elwi, Omar Almukhtar Tawfeeq, **Yahiea Alnaiemy** , Hayder S Ahmed, and Nagy Lajos. ”A UWB monopole antenna design based RF energy harvesting technology.” *Third Scientific Conference of Electrical Engineering (SCEE)*. IEEE, Iraq, , **2018**. 111-115.(WOS, Scopus, CiteScore=1.9)(Cited by 11).

- **Other publication**

[J9] Taha A Elwi, and **Yahiea Alnaiemy**. ”Nano-Scale Vee Yagi-UDA Antenna Based Nano Shell-Silver Coated Silica for Tunable Solid–State Laser Applications.” *Diyala Journal of Engineering Sciences*. Vol. 12, Issue 1, Pages 1-6, March (**2019**). (Cited by 1).

[J10] Taha A Elwi, and **Yahiea Alnaiemy**. ”Miniaturized Wide Band Folded Microstrip Antennas Based Metamaterials: Miniaturized Folded MSAs Based on MTM Theory and Techniques for Modern Wireless Applications.” *Scholars’ Press*, (**2018**). (Cited by 3).

[J11] **Yahiea Alnaiemy**. ”A Miniaturized Folded Microstrip Antenna Array for MIMO Applications Based Biomedical System.” *Diyala Journal of Engineering Sciences*. Vol. 9, Issue 1, Pages 18-27, March (**2016**).

[J12] Taha A Elwi, and **Yahiea Alnaiemy**. ”Electromagnetic characterizations of cement using free space technique for the application of buried object detection.” *Diyala Journal for Pure Science*. Vol. 11, Issue 4, Pages 1-10, July (**2015**). (Cited by 4).

[J13] Taha A Elwi, Ahmed Imad Imran, and **Yahiea Alnaiemy**. ”A miniaturized lotus shaped microstrip antenna loaded with EBG structures for high gain-bandwidth product applications.” *Progress In Electromagnetics Research (PIER)*. Vol. 60, Issue 4, Pages 157-167, (**2015**). (Cited by 26).

[J14] Amer H Al Habsi, **Yahiea Alnaiemy**, Hussain M. Al-Rizzo, Robert Akl, and Maytham M. ”Spectrally Efficient Modulation and Turbo Coding for Wireless Communication in Gaussian Channel.” *International Journal of Engineering and Innovative Technology (IJEIT)*. Vol. 3, Issue 8, Pages 40-47, Fab.(**2014**).

[J15] Amer H Al Habsi, **Yahiea Alnaiemy**, Hussain M. Al-Rizzo, Robert Akl, and Maytham M. ”Parity Assisted Decoding for QAM in AWGN Channels.” International *Journal of Engineering and Innovative Technology (IJEIT)*. Vol. 3, Issue 8, Pages 16-20, Fab.(**2014**).

[J16] Taha A Elwi, Z Abbas, Mohammed Noori, **Yahiea Alnaiemy**, Ethar Y Salih, and Marwa M Hamed. ”Conformal antenna array for MIMO applications.” *Journal of Electromagnetic Analysis and Applications*. Vol. 6, Issue 4, (**2014**).(Cited by 13).

[J17] **Yahiea Alnaiemy**. ”Design, Fabrication, and Testing of Microstrip Antennas.” BOOK,LAP *LAMBERT Academic Publishing*. April (**2013**).

[J18] **Yahiea Alnaiemy**, Taha A Elwi, Haider R Khaleel, Hussain Al-Rizzo. ”A systematic approach for the design, fabrication, and testing of microstrip antennas using inkjet printing technology.” *International Scholarly Research Notices (Hindawi)*. Vol. 2012, (**2012**).(Cited by 17)

[C8] Taha A Elwi, Hussain Al-Rizzo, **Yahiea Alnaiemy**, and Haider R Khaleel, . ”Miniaturized microstrip antenna array with ultra mutual coupling reduction for wearable MIMO systems.” *2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*. Pages 2198-2201, July (**2011**).(Cited by 16)

[C9] Haider R Khaleel, Hussain Al-Rizzo, Daniel G Rucker, and **Yahiea Alnaiemy**. ”Flexible printed monopole antennas for WLAN applications.” 2011 IEEE *International Symposium on Antennas and Propagation (APSURSI)*. Pages 1334-1337, July (**2011**).(Cited by 37).

Bibliography

[1] V. G. Veselago, "Electrodynamics of substances with simultaneously negative and," *Usp. Fiz. Nauk*, vol. 92, p. 517, 1967.

[2] A. Erentok and R. W. Ziolkowski, "A hybrid optimization method to analyze metamaterial-based electrically small antennas," *IEEE transactions on antennas and propagation*, vol. 55, no. 3, pp. 731–741, 2007.

[3] N. Engheta and R. W. Ziolkowski, *Metamaterials: physics and engineering explorations*. John Wiley & Sons, 2006.

[4] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE transactions on microwave theory and techniques*, vol. 47, no. 11, pp. 2075–2084, 1999.

[5] F. Yang and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: a low mutual coupling design for array applications," vol. 51, no. 10, pp. 2936–2946.

[6] C. Caloz and T. Itoh, *Electromagnetic metamaterials: transmission line theory and microwave applications*. John Wiley & Sons, 2005.

[7] S. Enoch, B. Gralak, and G. Tayeb, "Enhanced emission with angular confinement from photonic crystals," *Applied physics letters*, vol. 81, no. 9, pp. 1588–1590, 2002.

[8] R. Marqués, F. Martin, and M. Sorolla, *Metamaterials with negative parameters: theory, design, and microwave applications*. John Wiley & Sons, 2011, vol. 183.

[9] Y. Rahmat-Samii and H. Mosallaei, "Electromagnetic band-gap structures: classification, characterization, and applications," 2001.

[10] R. W. Ziolkowski and A. D. Kipple, "Causality and double-negative metamaterials," *Physical Review E*, vol. 68, no. 2, p. 026615, 2003.

[11] M. M. B. Suwailam, M. S. Boybay, and O. M. Ramahi, "Mutual coupling reduction in mimo antennas using artificial magnetic materials," in *2009 13th International Symposium on Antenna Technology and Applied Electromagnetics and the Canadian Radio Science Meeting*. IEEE, 2009, pp. 1–4.

[12] D. Sievenpiper, L. Zhang, R. F. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and techniques*, vol. 47, no. 11, pp. 2059–2074, 1999.

[13] R. W. Ziolkowski and A. D. Kipple, "Application of double negative materials to increase the power radiated by electrically small antennas," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 10, pp. 2626–2640, 2003.

[14] R. W. Ziolkowski, "Propagation in and scattering from a matched metamaterial having a zero index of refraction," *Physical Review E*, vol. 70, no. 4, p. 046608, 2004.

[15] ——, "Antennas and propagation in the presence of metamaterials and other complex media: Computational electromagnetic advances and challenges," *IEICE transactions on communications*, vol. 88, no. 6, pp. 2230–2238, 2005.

[16] M. Thevenot, C. Cheype, A. Reineix, and B. Jecko, "Directive photonic-bandgap antennas," *IEEE Transactions on microwave theory and techniques*, vol. 47, no. 11, pp. 2115–2122, 1999.

[17] R. Biswas, E. Ozbay, B. Temelkuran, M. Bayindir, M. Sigalas, and K.-M. Ho, "Exceptionally directional sources with photonic-bandgap crystals," *JOSA B*, vol. 18, no. 11, pp. 1684–1689, 2001.

[18] A. Lai, T. Itoh, and C. Caloz, "Composite right/left-handed transmission line metamaterials," *IEEE microwave magazine*, vol. 5, no. 3, pp. 34–50, 2004.

[19] B. A. Munk, *Frequency selective surfaces: theory and design*. John Wiley & Sons, 2005.

[20] T. Wu, "Frequency selective surface and grid array (a wiley interscience publication)," 1995.

[21] J. C. Vardaxoglou, *Frequency selective surfaces: analysis and design*. Research Studies Press, 1997.

[22] S. Hamdy and E. A. Parker, "Influence of lattice geometry on transmission of electromagnetic waves through arrays of crossed dipoles," in *IEE Proceedings H (Microwaves, Optics and Antennas)*, vol. 129, no. 1. IET, 1982, pp. 7–10.

[23] C.-H. Tsao and R. Mittra, "Spectral-domain analysis of frequency selective surfaces comprised of periodic arrays of cross dipoles and jerusalem crosses," *IEEE Transactions on antennas and propagation*, vol. 32, no. 5, pp. 478–486, 1984.

[24] E. Pelton and B. Munk, "A streamlined metallic radome," *IEEE Transactions on Antennas and Propagation*, vol. 22, no. 6, pp. 799–803, 1974.

[25] F. Bayatpur and K. Sarabandi, “A tunable metamaterial frequency-selective surface with variable modes of operation,” *IEEE transactions on microwave theory and techniques*, vol. 57, no. 6, pp. 1433–1438, 2009.

[26] G. V. Eleftheriades and K. G. Balmain, *Negative-refraction metamaterials: fundamental principles and applications*. John Wiley & Sons, 2005.

[27] A. R. Brown and G. M. Rebeiz, “A varactor-tuned rf filter,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, no. 7, pp. 1157–1160, 2000.

[28] R. Ziolkowski and A. Erentok, “At and below the chu limit: passive and active broad bandwidth metamaterial-based electrically small antennas,” *IET Microwaves, Antennas & Propagation*, vol. 1, no. 1, pp. 116–128, 2007.

[29] I. Glover and P. M. Grant, *Digital communications*. Pearson Education, 2010.

[30] A. Eldek, A. Abdallah, and M. Manzoul, “Reconfigurable microstrip double-dipole antennas for personal wireless communications,” 2011.

[31] J.-S. Row and Y.-H. Wei, “Wideband reconfigurable crossed-dipole antenna with quad-polarization diversity,” vol. 66, no. 4, pp. 2090–2094, conference Name: IEEE Transactions on Antennas and Propagation.

[32] J. T. Bernhard, “Reconfigurable antennas,” *Synthesis lectures on antennas*, vol. 2, no. 1, pp. 1–66, 2007.

[33] Y. Yashchyshyn, “Reconfigurable antennas by RF switches technology,” in *2009 5th International Conference on Perspective Technologies and Methods in MEMS Design*. IEEE, 2009, pp. 155–157.

[34] Z. A. Hassain, A. R. Azeez, M. M. Ali, and T. A. Elwi, “A modified compact Bi-directional UWB taperd slot antenna with double band-notch characteristics,” *Advanced Electromagnetics*, vol. 8, no. 4, pp. 74–79, 2019.

[35] H. Wang, Z. Wu, Y. Wang, C.-Y.-D. Sim, G. Yang *et al.*, “Small-size folded monopole antenna with switchable matching circuit for ultra-thin mobile applications,” *Progress In Electromagnetics Research*, vol. 65, pp. 131–138, 2016.

[36] S. Henthorn, K. L. Ford, and T. O’Farrell, “Bit-error-rate performance of quadrature modulation transmission using reconfigurable frequency selective surfaces,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2038–2041, 2017.

[37] W. Tang, J. Y. Dai, M. Chen, X. Li, Q. Cheng, S. Jin, K.-K. Wong, and T. J. Cui, “Programmable metasurface-based rf chain-free 8PSK wireless transmitter,” *Electronics Letters*, vol. 55, no. 7, pp. 417–420, 2019.

[38] B. Liang, B. Sanz-Izquierdo, E. A. Parker, and J. C. Batchelor, "A frequency and polarization reconfigurable circularly polarized antenna using active EBG structure for satellite navigation," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 1, pp. 33–40, 2014.

[39] D. K. Singh, B. K. Kanaujia, S. Dwari, G. P. Pandey, and S. Kumar, "Reconfigurable circularly polarized capacitive coupled microstrip antenna," *International Journal of Microwave and Wireless Technologies*, vol. 9, no. 4, p. 843, 2017.

[40] S. M. Saeed, C. A. Balanis, and C. R. Birtcher, "Inkjet-printed flexible reconfigurable antenna for conformal WLAN/WiMAX wireless devices," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1979–1982, 2016.

[41] A. Babakhani, D. B. Rutledge, and A. Hajimiri, "Transmitter architectures based on near-field direct antenna modulation," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 12, pp. 2674–2692, 2008.

[42] B. Mohamadzade, R. B. Simorangkir, S. Maric, A. Lalbakhsh, K. P. Esselle, and R. M. Hashmi, "Recent developments and state of the art in flexible and conformal reconfigurable antennas," *Electronics*, vol. 9, no. 9, p. 1375, 2020.

[43] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications," *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2250–2261, 2012.

[44] E. Dahlman, Y. Jading, S. Parkvall, and H. Murai, "3G radio access evolution—HSPA and LTE for mobile broadband—," *IEICE transactions on communications*, vol. 92, no. 5, pp. 1432–1440, 2009.

[45] M. Yousefbeiki, O. N. Alrabadi, and J. Perruisseau-Carrier, "Efficient MIMO transmission of PSK signals with a single-radio reconfigurable antenna," *IEEE transactions on communications*, vol. 62, no. 2, pp. 567–577, 2014.

[46] W. Yao and Y. E. Wang, "An integrated antenna for pulse modulation and radiation," in *Proceedings. 2004 IEEE Radio and Wireless Conference (IEEE Cat. No. 04TH8746)*. IEEE, 2004, pp. 427–429.

[47] M. Manteghi, "A wideband electrically small transient-state antenna," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 4, pp. 1201–1208, 2016.

[48] G. I. Kiani and T. S. Bird, "ASK modulator based on switchable FSS for THz applications," *Radio Science*, vol. 46, no. 02, pp. 1–8, 2011.

[49] S. Henthorn, K. L. Ford, and T. O'Farrell, "Direct antenna modulation for high-order phase shift keying," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 1, pp. 111–120, 2019.

[50] S. Srivastava and J. J. Adams, "Analysis of a direct antenna modulation transmitter for wideband OOK with a narrowband antenna," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 10, pp. 4971–4979, 2017.

[51] Y. Alnaiemy, T. A. Elwi, and L. Nagy, "Mutual coupling reduction in patch antenna array based on EBG structure for MIMO applications," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 63, no. 4, pp. 332–342, 2019.

[52] Y. Alnaiemy and L. Nagy, "Design of a controllable antenna based on embedded differential PSK modulation," vol. 90, pp. 43–62, publisher: EMW Publishing. [Online]. Available: http://www.jpier.org/pierb/pier.php?paper=20100106

[53] C. A. Balanis, *Antenna theory: analysis and design*. John wiley & sons, 2016.

[54] X. Chen, B.-I. Wu, J. A. Kong, and T. M. Grzegorczyk, "Retrieval of the effective constitutive parameters of bianisotropic metamaterials," *Physical Review E*, vol. 71, no. 4, p. 046610, 2005.

[55] H.-Y. Yao, J. L.-W. Li, Q. Wu, and J. A. Kong, "Macroscopic performance analysis of metamaterials synthesized from micrsocopic 2-d isotropic cross split-ring resonator array," *Progress In Electromagnetics Research*, vol. 51, pp. 197–217, 2005.

[56] F. Yang and Y. Rahmat-Samii, *Electromagnetic band gap structures in antenna engineering*. Cambridge university press Cambridge, UK, 2009.

[57] L. Solymar and E. Shamonina, *Waves in metamaterials*. Oxford University Press, 2009.

[58] S. Clavijo, R. E. Diaz, and W. E. McKinzie, "Design methodology for sievenpiper high-impedance surfaces: An artificial magnetic conductor for positive gain electrically small antennas," *IEEE transactions on antennas and propagation*, vol. 51, no. 10, pp. 2678–2690, 2003.

[59] B. Allen, M. Dohler, E. Okon, W. Malik, A. Brown, and D. Edwards, *Ultra-Wideband Antennas and Propagation: For Communications, Radar and Imaging*. John Wiley & Sons, 2006.