Workshop Program

8:30-10:30  System Aspects
Chairman  Dieter Jäger

8:30-8:55  Optical Processing and Transmission of Subcarrier Multiplexed Microwave Signals
Tibor Berceli¹, Attila Hilt², Gabor Jaró¹, Ghislaine Maury³
¹ Technical University of Budapest, Hungary
² Innovations Company for Telecommunication, Hungary
³ Institut National Polytechniques de Grenoble, France
berceli@mht.bme.hu

8:55-9:20  A Fiber Optic Wireless Local Area Network in the 60 GHz Band
Michael Sauer, Konstantin Kojucharow, Heiko Kaluzni, Michael Otto, Christian Schaeffer
Technische Universität Dresden, Germany
schae@ifn.et.tu-dresden.de

9:20-9:45  Full-Duplex 60-GHz Fibre-Wireless Networks employing EA-Transceiver
Andreas. Stöhr¹, Robert Heinzelmann¹, Toshiaki Kuri², Ken-ichi Kitayama³, Dieter Jäger¹
¹ Gerhard-Mercator University, Duisburg, Germany
² Communication Research Laboratory, Tokyo, Japan
³ Osaka University, Japan
stoehr@uni-duisburg.de

9:45-10:10  Why can’t I buy a Fibre Supported mm-wave System
Phil Lane
University College London, UK
p.lane@ee.ucl.ac.uk

10:10-10:35  Microwave Photonics in Defense Systems
François Deborgies
Thomson-CSF, Orsay Cedex, France
deborgie@lcr.thomson-csf.com

10:35-11:00  Coffee Break

11:00-12:45  Photonic Devices I
Chairman  Tibor Berceli

11:00-11:30  A Cascade InP HBT Optomixer
Y. Betser, A. Madjar, D. Ritter
Technion - Israel Institute of Technology, Haifa, Israel
asher@tx.technion.ac.il, madjar@rafael.co.il

10:30-11:55  A Model of Heterojunction Phototransistor for the Design of Opto-Microwave Amplifiers and Mixers
C. Rumelhard
CNAM, Paris, France
rumelhard@cam.fr
11:55-12:20 InP/InGaAs Bipolar Phototransistor as a Front-end Photoreceiver for HFR Distribution Systems
C. Gonzalez
OPTO+ Groupement d'Intérêt Économique, Marcoussis Cedex, France
carmen.gonzalez@cnet.francetelecom.fr

12:20-12:45 Polarization Independent, High Efficiency Four-Wave Mixing in Semiconductor Optical Amplifiers for Frequency Conversion
Paolo Spano
Fondazione Ugo Bordoni Rome, Italy
Pspano@fub.it

12:45-14:00 Lunch

14:00-15:30 Photonic Devices II
Chairman Asher Madjar

14:00-14:30 Recent Developments in Microwave Photonic Devices
Dieter Jäger
Gerhard-Mercator University, Duisburg, Germany
D.Jaeger@OE.Uni-Duisburg.de

14:30-15:00 Transition Structures for Photonic to Microwave Conversion
N. Kaneda, T. Chu, M. Wu and T. Itoh
UCLA Los Angeles, USA.
itoh@ee.ucla.edu

15:00-15:30 A Circuit Point of View on Microwave Photonic Devices
Andre Vander Vorst, M. Serres, B. Stockbroeckx, I. Huynen
Universite Catholique de Louvain, Belgium
VanderVorst@emic.ucl.ac.be

15:30-15:45 Coffee Break

15:45-17.00 Photonic Devices III
Chairman Andreas Stöhr

15:45-16:10 The Predicted Performance of an Electro-Absorption Artificial Transmission Line Optical Modulator
Colin S. Aitchison
University of Surrey, UK.
Colin.Aitchison@brunel.ac.uk
16:10-16:35  Arrayed Light Modulators as Receiving Antennas
Masayuki Izutsu
Communication Research Laboratory, Tokyo, Japan
Izutsu@crl.go.jp

16:35-17:00  Optical Delay Network Structure for 10 GHz True Time Delay Antennas Using
Semiconductor Laser Amplifiers as Optical Switching Gates
R. Eggemann, G. Grosskopf, E. Patzak, D. Rohde
Heinrich Hertz Institut Berlin, Germany
grosskopf@hhi.de
OPTICAL PROCESSING AND TRANSMISSION OF SUBCARRIER MULTIPLEXED MICROWAVE SIGNALS

Tibor Berceli\(^1,2\), Attila Hilt\(^2,1\), Gábor Járó\(^1\), Ghislaine Maury\(^3\)

\(^1\) Technical University of Budapest, Hungary
\(^2\) Innovations Company for Telecommunication, Hungary
\(^3\) Institut National Polytechnique de Grenoble, France
berceli@mht.bme.hu

Abstract - The subcarrier transmission of microwave signals is a perspective method for the optical fiber links. Several approaches are presented covering the generation and reception of the subcarrier optical signals. The transmission problems like linearity, distortion, chromatic dispersion, etc. are also discussed. The optical-microwave mixing process is utilized for an improved reception.

I. Introduction

There is an increasing demand for better and more communication services all over the world. In this progress the main transmission medium is the optical fiber offering an enormous bandwidth along with low attenuation and light weight. However, this huge transmission capacity cannot be fruitfully exploited due to the capacity limitations of the photonic and electronic components of the fiber optic link [1-4].

For increasing the transmission capacity two approaches are at our disposal. One method applies higher and higher bit rates like 2.5-10-40 Gbit/s to provide increased capacity. This method is well applicable for the backbones of the communication networks which are mainly used as point-to-point connections. However, this approach is not well suited to distribution/collection systems or local area networks where point-to-multipoint or multipoint-to-multipoint connections are required.

In these applications the problem arises from the fact that a high speed system requires high bit rate components everywhere in the system what is a big drawback if the number of terminals is high. Another disadvantage is that every signal processing unit of the system should have the highest foreseen capacity in the time of installation. All of these units have to be replaced if the capacity has to be increased or parallel transmission channels have to be installed utilizing the wavelength division multiplexing (WDM) principle. However for the WDM system more sophisticated photonic components (tunable lasers, optical filters, wavelength converters, selective receivers, etc.) are to be applied making the system more expensive.

In the other method the multiplexing is performed in the electronic region instead of the optical region. Therefore it applies subcarriers with different frequencies and low bit rate (2, 8, 34 or 140 Mbit/s) channels on each subcarrier. The subcarrier multiplexed (SCM) system offers many advantages: inserting or dropping a channel is easy, therefore point-to-multipoint or multipoint-to-multipoint connections can be established using inexpensive electronic components. The capacity of the system is enchanced by introducing new subcarrier frequencies. The bit rate is relatively low therefore the system is well suited to the distribution and collection of information and for local area networks (LANs). Multiplexing the channels is accomplished in the electronic region what is less expensive than optical multiplexing.

In this paper the SCM optical system is discussed in the detail. Its main application fields are:
- distribution of entertainment programs (TV, radio, music, etc.),
- broadcasting public information (teleeducation, journals, announcements, traffic timetables, weather forecasts, etc.),
- collection of data (telemetering, telecontrol, etc.),
- multipoint-to-multipoint communications (voice, data, picture etc.),
- cellular mobile networks,
- indoor communications,
- integrated services systems.

For the different applications different system architectures are preferable, and different problems are encountered.

II. Distribution system

In a distribution system a center station distributes information for the terminals of many subscribers. The reception can be full or selective. Therefore the different channels are put on different subcarriers and
this way the subscribers can receive any or all of the channels.

The multi-subcarrier transmitter has to meet some special requirements like: high linearity, broad bandwidth, low noise, high dynamic range and low distortion. As the intensity modulation is applied the wavelength stability is not critical because at the reception only the intensity of the optical beam is detected.

**Linearity**

The linearity of a direct modulated laser diode is usually not high enough for a multi-carrier modulation. To improve the modulation linearity there are two main methods: the laser diode inner construction can be properly designed to get a higher linearity or the nonlinearity of the laser can be equalized utilizing different compensation approaches.

As the availability of high linearity laser diodes is limited in many cases a compensation method is to be applied. The best results are obtained by the active matching techniques which offers an adaptive behaviour as well [5].

In Fig. 1 the modulation characteristics of a direct modulated laser diode are presented for two cases. The upper curve of the figure shows the modulation characteristics using passive matching and its lower curve presents the result of the linearization applying the active matching method. As seen a very high linearity is achieved in a wide modulation range.

![Graph showing optical output power versus driving voltage](image)

**Distortion**

The linearity is also checked by measuring the harmonic distortion. Fig. 2 shows the fundamental second and third harmonics as a function of the modulation signal power. The achieved linearity is high enough, if the power of the modulation signal is below a certain level. This power level is dependent on the specific application. For a higher number of subcarriers a higher linearity is required to keep the third order intermodulation product below the specification.

The third order intermodulation distortion has been tested using 4 subcarriers to modulate the intensity of Fabry-Perot (FP) and distributed feedback (DFB) lasers. The results are presented in Table 1. The measurement is performed with and without an optical isolator. To achieve a very low intermodulation product the optical reflections should be also very low, below -60 dB.

![Graph showing output level of the fundamental, second and third harmonic frequency signals](image)

<table>
<thead>
<tr>
<th>Laser type</th>
<th>DFB</th>
<th>Fabry-Perot</th>
</tr>
</thead>
<tbody>
<tr>
<td>With isolator</td>
<td>79 dBc</td>
<td>79 dBc</td>
</tr>
<tr>
<td>Without isolator</td>
<td>71 dBc</td>
<td>71 dBc</td>
</tr>
</tbody>
</table>

Table 1. Third order intermodulation products

In case of a large number of subcarriers another test method is used: the matrix generator. This generator provides a large number of signals except two: one close to the lower edge of the total band and one close to the upper edge of the total band. This composite signal is used to modulate the laser. In the receiver a special filter is applied which has stop band for every signals of the matrix generator and two pass-bands where there are no modulating signals.

First the matrix generator is switched off. Then the receiver gets only noise in the two pass-bands. In the next step the matrix generator is switched on. In this case the total distortion is measured in the pass-bands which is the result of every intermodulation of all signals. During the test the total modulation power is varied, and thus the optical modulation depth is adjusted considering the allowable total distortion.
III. Multipoint-to-multipoint system

In a multipoint-to-multipoint system each terminal wants to communicate with any other terminal in the network or via a gate-way with an external terminal. The principle of this type of system is shown in Fig. 3. The optical transmitters and receivers of the terminals are connected by a passive optical network (PON) composed of optical hybrids and couplers. The network contains a control unit to establish the requested connection. Each optical transmitter has its own subcarrier frequency and in the optical receivers the wanted subcarrier is selected to establish the connection. A common channel is used for signaling and control.

![Diagram](image)

Fig. 3. Optical data communication network

Each optical terminal can serve as a traffic concentrator. In that case a TDMA (time division multiple access) method is used to connect several subscribers to the optical terminal.

**Combined wireless-optical system**

A simple and economical system can be established applying subcarrier multiplexing (SCM) and time division multiplexing (TDM) simultaneously.

![Diagram](image)

In that case the center station is only a controlling and signaling unit in the network and switching is actually done by the selection of the subcarrier frequency and the time slot.

This system offers optimum solution for the local area network of an office building. In this system wireless communications is used in the office rooms serving the different terminals. Each large room or a group of neighbouring small rooms has its own wireless network and thus the transmitter power can be small enough because there is no need to establish connections by radio waves through many walls. The individual wireless networks use TDMA (time division multiple access) techniques. They are interconnected via optical fibers applying the subcarrier multiplexing method.

The combined wireless-optical communications offers several further benefits for the customers. The optical networking is expensive if it connects all the terminals. However, in this application its cost is low because it is applied only in the highways of the network. On the other hand the wireless section becomes more economic due to the small area of a picocell. The system is very flexible, it can easily be extended to serve more terminals including mobiles as well.

The new architecture takes advantage of the very wide transmission band offered by optical fibers. Thus a huge number of subcarriers can be accommodated providing a high traffic capacity. The subcarrier multiplexed transmission also offers a high flexibility for changing traffic conditions.

The block diagram of the new system is presented in Fig. 4. Each large office room or a group of adjacent small rooms has a specific carrier frequency for the terminal radio transmitters and the terminal radio receivers are tuneable.

![Diagram](image)

Fig. 4. Block diagram of the combined system
The modulation methods can be FSK (frequency shift keying), BPSK (binary phase shift keying), QPSK (quadrature phase shift keying), 16 QAM (16 state quadrature amplitude modulation), etc. depending on the wireless links because the optical part of the system is transparent. The transmitter signals of the terminals are collected by the receiver of the radio node and they are transmitted via the optical fiber. This way the radio carriers are used as subcarriers in the optical region.

The optical fiber operates as a one-way bus using the principle of collection and distribution. When all the subcarriers are transposed into the optical region the fiber is routed back to the radio nodes where all of the channels are converted back into the radio frequency region. However, before radiation their frequencies should be shifted to use a different frequency band for the radio up-link and down-link. The route from the terminal to the radio node is called up-link, and the route from the radio node to the terminal is called down-link.

The number of the terminals is determined basically by the available radio frequency bandwidth. Assuming 2 Mbit/s bit rate for every subcarrier and FSK (frequency shift keying) modulation of the radio waves, 90 subcarriers can be accommodated in a 200 MHz frequency band keeping 10 % bandwidth for the separation of the channels. That means the number of the simultaneously operated simplex channels is 2700 if their bit rate is 64 kbit/s. This way the network can provide a high quality of service for at least 10000 terminals with 64 kbit/s bit rate assuming 13.5 % simultaneous traffic (or availability) in the network.

Naturally, some channels are used for connections to the public switched network and to other local area networks. In many cases the bit rate can be smaller resulting in a higher number of simultaneously operating channels. Utilizing the total available bandwidth, i.e. 2 GHz the number of channels can be almost 10 times higher. This very high capacity is usually not needed, however, it can be utilized for broadband communications services.

IV. Cellular mobile networks utilizing fiber optic links

In a cellular mobile network the fiber connection can be applied in two different ways:
- the information channels are transmitted over the fiber and the carrier frequency is generated locally at the radio base stations.
- the information channels and the carrier frequencies are transmitted together over the fiber to the radio base stations (radio over fiber system).

In the first case the optical transmission has less troubles however, the carrier frequencies are not synchronized. In the second case the radio base station has less functions. The carrier frequencies are synchronous, but the fiber transmission is more complicated. Nevertheless, the second method offers many advantages mainly in the millimeter wave region. Here we discuss this approach in more detail.

There are several methods for the radio over fiber approach.

In one approach two lasers are used with off-set frequency stabilization. Their frequency difference is kept constant utilizing a millimeter wave signal as a reference. For the stabilization one of the lasers is tuned by a phase locked loop. This way the frequency difference between the two laser beams is in the millimeter wave region. These two beams are transmitted via a fiber to the radio base stations where the millimeter wave signal is regained by optical detection.

In another approach a single laser operating in two modes is applied. The frequency difference between the two laser modes is kept constant by injection locking techniques utilizing a millimeter wave signal.

In a third approach a single mode laser beam is modulated by the millimeter wave signal. This method seems to be simpler than the previous two ones, however, it needs a high frequency external modulator what is rather expensive. A further problem arises in the transmission of the optical wave carrying a millimeter wave signal. Due to the chromatic dispersion of the fiber transmission minima are obtained for longer fiber lengths. This problem may be overcome by the use of several modulation techniques at the transmitter end which effectively mitigate the effect of the fiber chromatic dispersion, such as single-side-band modulation [6,7], minimum transmission bias or maximum transmission bias of the MZ modulator [8]. However, the single-side-band modulation is more complex while at the minimum or maximum transmission bias the modulation linearity is poor.

For the optical generation of a stable, low noise signal based in the first approach DFB lasers are used which have a low relative intensity noise (RIN) and can be tuned to accomplish the off-set frequency stabilization. For the second approach a two-mode laser with a low RIN is needed along with a high mode purity and stability. In the third approach a high frequency external modulator is necessary.

Beside these requirements the millimeter wave signal – used as a reference of the phase locked loop
for off-set frequency stabilization in the first approach, or for injection locking of the two-mode laser in the second approach, or for external modulation of the single-mode laser in the third approach - has to be stable and of very low noise as well. Further at the reception side a high-speed photodiode is to be applied [9]. Therefore, these methods are very complex and expensive.

Nevertheless, there is an increasing need for higher frequencies and thus carrier frequencies in the millimeter wave band are to be used in cellular mobile communication systems as well. The optical transmission of millimeter waves faces many obstacles. Thus the optical transmission of signals is more and more lossy when the frequency is increased.

**Novel optical signal generation methods**

The common basic principle of these methods is that a low frequency reference signal is transmitted to the radio base stations instead of the millimeter wave signal and utilizing this low frequency reference the millimeter wave signal is generated at the radio base stations [10,11].

In this approach a single mode laser is intensity modulated by the sub-harmonic reference signal. The detected signal is used to stabilize the VCO frequency by a phase locked loop [12,13]. Beside the reference signal subcarriers are used for the optical transmission of the information channels. The block diagram of the system is shown in Fig. 5.

The main task is to ensure the low noise property of the millimeter wave signal. Comparing the well-known methods and the present method it is obvious that the electronic system part producing the millimeter wave signal provides the same stability and noise performance when it is applied either in the optical transmitter or in the optical receiver. Therefore it is very relevant to use a low noise quartz crystal oscillator as the basic source for the reference signal.

![Fig. 5 The block diagram of the optically fed cellular radio system](image)

**Phase jitter measurements**

A measurement setup has been developed to eliminate the phase jitters originating from the generators used for down-converting the millimeter wave signal.

An IQ demodulator operating at 885 MHz was utilized, and the millimeter wave signal was down-converted into this band by a mixer. The I and Q signals were displayed on an oscilloscope and the phase jitter distribution was recorded and calculated by a computer.

The distribution has 2.25° standard deviation. As the reference signal has a phase jitter of \( \approx 0.09° \) and the multiplication number of the frequency is 24, the noise contribution of the system is negligible. Fig. 6 shows the phase histogram compared to the Gaussian distribution.

![Fig. 6 Phase distribution of I/Q signal](image)

**Bit error rate measurements**

In these tests the bit error rate of the whole system was measured in case of different modulations. In
modulation test the system performance has been evaluated with changing signal to noise ratio of the radio frequency signal (see Fig. 7). The curve for MODEM refers to the back-to-back MODEM measurement. The curve of ELECTRICAL test gives the data for the case when direct electrical connection was between the center station and the radio base station. Finally, the curve of OPTICAL transmission show a very small degradation compared to the ELECTRICAL connection.

V. Chromatic dispersion effects

Based on a coherent model of the fiber-optical link we developed a general simulation tool for studying different optical link architectures. Fig. 8 shows the detected power of the optically transmitted signal using classical externally modulated optical link. The effect of chromatic dispersion is clearly seen resulting in periodic rejections as a function of fiber length L and modulation frequency $f_{RF}$.

**Special modulation modes**

To avoid chromatic dispersion, several proposals have been reported [14,15]. Fig. 9 plots suppressed carrier optical modulation (SC-OM) achieved by a normalized modulator bias of $\gamma = V_{DC}/V_{p}=1$. At this special bias 2nd harmonic of the 12 GHz modulation signal is generated. Advantageously, SC-OM is unaffected by chromatic dispersion.

Single sideband optical modulation (SSB-OM) offers a further perspective solution of dispersion-free optical transmission of MW/MMW signals at 1.55 μm. One SSB-OM method filters out optically one of the sidebands [16].

![Figure 8. Detected power level of MW signal transmitted optically in dispersive fiber. (Linear modulator bias of $\gamma=0.5$, $\alpha=0.25$, $D=17$ ps/km/nm, $R_{pp}=0.35$ A/W)](image)

Another solution uses dual-electrode optical modulator [6,7]. The MW modulation signal is splitted into two parts, and a $\theta = 90^\circ$ phase difference is introduced between them. As presented in Fig. 10 at $\gamma=0.5$ lower sideband optical modulation (LSB-OM) while at $\gamma=1.5$ upper sideband optical modulation (USB-OM) is generated. Fig. 11 shows the detected first harmonic power level as a function of modulation frequency $f_{RF}$ and fiber length L, respectively. The modulator bias $\gamma=0.5$ and $\theta=90^\circ$ to achieve ideal SSB-OM. It is worth to compare Fig. 11 to Fig. 8. detected level has somewhat decreased but rejections are avoided.

![Figure 9. Detected 2nd harmonic level after transmission on dispersive fiber. ($f_{RF} = 12$ GHz, $\alpha=0.25$, $D=17$ ps/km/nm, $R_{pp}=0.35$ A/W )](image)
transmitted via a fixed frequency subcarrier, and therefore a fixed filter is used the signaling channel.

Mixing of optical waves and microwaves offers new perspectives for the reception of subcarrier multiplexed optical signals [17-20]. In the subcarrier type optical data communications each transmitter has its own subcarrier frequency as it is shown in Fig. 14. The transmission capacity of the network can be increased by applying new subcarriers, and thus the digital processing rate per subcarrier remains fixed.

Fig. 14. Subcarrier signal transmission (transmitter)

Utilizing the optical-microwave double mixing method in a receiver of a subcarrier multiplexed signal transmission (Fig. 15) a simple receiver structure and channel selection can be achieved.

Fig. 15. Subcarrier signal transmission (receiver with optical-microwave mixing)
VII. Optical-microwave mixing by a photo-diode

Photo-detection investigation

Before the mixing experiments, the optical detection was characterized. The investigated photodiode was an 1A358 type CATV PIN photodiode. This detection response was used as a reference. In this arrangement the dynamic behavior of the photodiode (PD) in its detection mode of operation was investigated. The intensity modulated optical signal is generated by a HP 83424A 1550 nm DFB laser source and a HP 83422A external Mach-Zehnder optical modulator, with a typical optical modulation depth (OMD) of 25%.

The detected intensity modulated optical signal was measured by a spectrum analyzer. The response of the diode was flat up to 3 GHz and the detected signal level at high reverse bias voltage was ≈ -36 dBm (@200 MHz).

Optical-microwave double mixer

The developed new optical-microwave mixing setup is shown in Fig. 16. The local oscillator (LO) signal is fed to the photodiode via a circulator [21]. A wideband circulator is used to separate the input LO signal and the output mixing product.

The high impedance in the baseband is generated by a resonator circuit constructed by inductors and capacitors (L_r, C_r, L_p, C_p). The resonator inductance is L_r. The parallel resonator (L_p, C_p) in the series branch constitutes a branching filter and it is tuned at the resonance (baseband) and in a narrow band determined by the quality factor of the resonator it shows a high input impedance thus it separates the photodiode from the Z_0 system impedance. This high impedance and the remaining resonator elements with the photodiode capacitance can produce the desired high impedance. With proper values of the resonators the attenuation of the embedding circuit in the LO and up-converted signal band can be negligible.

![Fig. 16 Mixing measurement setup with electrical LC resonators](image)

The measured lower sideband of the upconverted signal is shown in Fig. 17. The used circulator has a bandwidth of 2-4 GHz. The optical carrier was modulated by a f_mod = 10 - 410 MHz signal. The local oscillator signal has a 5 dBm power at 2.5 GHz frequency. The reverse bias of the photodiode was varied 0 - 1.5 V in 0.1 V steps. The horizontal axis of the surface plot in Fig. 17 is the frequency offset from the 2.5 GHz carrier, the perpendicular axis shows the reverse bias of the photodiode and the vertical scale is the power level of the up-converted signal. The surface has a maximum edge at about 0.2 V reverse biased voltage. The up-converted spectrum has a -2.89 dBm peak at the modulation frequency of 289 MHz. This peak overcomes the detected level by more than 30 dB.

![Fig. 17. Lower sideband of the upconverted signal using series and parallel resonance P_{LO} = 5 dBm (maximum -2.89 dBm @ 289 MHz)](image)

The noise properties of the optical-microwave mixing effect were also investigated. The theoretical investigation shows that the equivalent input noise density of the mixer is 0.15 pA/Hz^{1/2}. The measured output noise spectral density of the mixer is -141.7 dBm/Hz at 270 μW illumination without modulation.

VIII. Optical microwave-mixing by an interferometer

We present now a new technique for remote up-conversion by inserting a passive all-optical device in the microwave (MW) fiber-optic link. Using a semiconductor laser directly modulated by two MW signals and an unbalanced Mach-Zehnder interferometer (UMZ) to convert optical frequency modulation (FM) into intensity modulation (IM), mixing is achieved after photo-detection [22].

Experiments with a UMZ integrated on glass-substrate have demonstrated the feasibility of this optical method for MW mixing with a low cost device of easy fabrication. Temperature control of the device allows optimized mixing performance and response.
This method permits to overcome the effect of chromatic dispersion in standard single-mode fiber systems operating in the 1.55 μm wavelength window [23]. Due to the presence of high-frequency fundamental components in the optical field, the received power is considerably degraded during transmission and direct detection in conventional systems, using either direct or external modulation in the MW band. With the proposed technique, lower frequency components of the field can be transmitted. The insertion of the simple UMZ generates high frequency only at detection side, therefore the available fiber length is extended. As it is shown by simulation results, this method can be used for the upconversion of MW subcarriers carrying digital signals.

We have particularly investigated the case of transmission and distribution of digital MW and MMW signals in fiber-optic networks that operate at λ=1550 nm. In such systems, the effect of chromatic dispersion during transmission drastically degrades the high-speed detected signals and remote frequency upconversion is a technique to overcome this problem. To validate our method we realized an interferometer integrated on glass-substrate and experimental results show good agreement with theory.

Our method permits to minimize the effect of chromatic dispersion in standard single-mode fiber systems operating in the 1.55 μm wavelength window. This effect significantly limits the transmission distance in intensity modulated (IM) optical links operating at MW frequencies and using either direct or external modulation: due to the presence of three main spectral components in the optical field (the optical carrier and the two sidebands corresponding to the high-frequency fundamental) the received power is considerably degraded during transmission and direct detection in the conventional systems. A several km long fiber-optic link can completely filter the MW signal. The rejections are periodic as a function of fiber length and these periods are shorter and shorter as the modulation frequency is increased.

As already explained, with the proposed technique the LD is directly modulated by two lower frequencies \(f_{LO}\) and \(f_{RF}\). The optical field emitted by the LD contains all their harmonics and intermodulation products. But at the output of the UMZ, at minimum of transmission, the optical carrier is suppressed. Two main spectral components (around \(f=f_{op}=f_{LO}\)) remain, at lower frequency than in the classical solutions where the optical field would be directly modulated by a single signal at \(f\) (since \(f=f_{LO}+f_{RF}\)). The insertion of the simple UMZ generates high frequency only at the detection side. Therefore, chromatic dispersion has less effect and the available fiber length is extended.

Fig. 18 Detected level of the mixing frequency \(f_{mix}=6\) GHz with \(f_{LO}=1.5\) GHz, \(f_{RF}=4.5\) GHz, \(m_{LO}=m_{RF}=0.15\) vs. fiber length and interference regime

Dispersion sensitivity has been investigated by simulations supposing \(D=17\) ps/km/nm fiber dispersion at \(\lambda=1.55\) μm. Calculations are very easy in Fourier domain because the optical field spectrum at the output of the fiber is simply calculated by multiplying the optical field spectrum at its input by the transfer function of the optical fiber, as it has already been done in the case of the UMZ. We can also note that the fiber and the UMZ act both as linear filters and if we neglect other problems like polarization effects, the position of the UMZ at the input or at the output of the fiber does not matter.

Fig. 18 shows mixing frequency power level after quadratic photodetection as a function of the fiber length and the interference regime. As expected, the period of rejections of the power detected is greater at minimum of transmission. The system using UMZ is less sensitive to chromatic dispersion than a classical optical link with direct LD modulation at 6 GHz: the period of rejection is multiplied by 2.

**IX. Conclusions**

The subcarrier transmission of microwave signals is a perspective method for the optical fiber links. Several approaches have been presented covering the generation and reception of the subcarrier optical signals. The transmission problems like linearity, distortion, chromatic dispersion, etc. have also been discussed. The effect of optical modulation methods on the chromatic dispersion have been presented as well. The optical-microwave mixing process has been utilized for an improved reception.
X. Acknowledgements

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References


