A NEW OPTICAL SIGNAL DISTRIBUTION METHOD FOR PHASED ARRAY ANTENNAS AT MILLIMETRE WAVES

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Abstract

The optical beam forming of phased array antennas is a very promising technique because of the advantages of the fibre optic signal transmission and the optical control of microwave monolithic integrated circuits (MMICs). In this paper a new approach is presented for the optical generation of millimetre waves (MMW) with the intention to feed the phased array antennas in radar systems. In this approach an optically transmitted subharmonic reference signal is used to stabilise a voltage controlled harmonic oscillator providing the millimetre wave signal. This method provides a simple and inexpensive new approach.

Introduction

The optical beam forming of phased array antennas is a very promising technique because of the advantages of the fibre optic signal transmission and the optical control of MMICs. In phased array antennas one of the most important tasks is the signal distribution for the T/R (transmit/receive) modules. Performing this task the main requirements are: a high frequency-stability, low amplitude and phase noise, agile frequency switching, fast amplitude and phase control, and MMIC compatibility. There are three well-known approaches to generate millimetre waves by optical methods for phased array antennas [1, 2].

In the first approach two lasers are used with off-set frequency stabilisation. Their frequency difference is kept constant utilising a millimetre wave signal as a reference. For the stabilisation one of the lasers is tuned by a phase locked loop. This way the frequency difference between the two laser beams is in the millimetre wave region. These two beams are transmitted via a fibre to the T/R modules where the millimetre wave signal is regained by optical detection. In some cases the frequency of the millimetre wave signal has to be swept. That can be achieved by using a swept frequency synthesiser as a reference for the off-set stabilisation of the two lasers. However, sweeping the frequency of a stable and low noise synthesiser in the millimetre wave region is a rather difficult task.

In the second 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 utilising a millimetre wave signal. In this case sweeping the generated millimetre wave signal is almost impossible because the locking bandwidth of a two-mode laser is rather limited if the low noise requirement has to be met.

In the third approach a single mode laser beam is modulated by the millimetre 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 millimetre wave signal. Due to the chromatic dispersion of the fibre transmission minima are obtained for longer fibre lengths. This problem is discussed in more detail in the Appendix.

For the optical generation of a stable, low noise signal based on the first approach distributed feedback (DFB) lasers are used which have a low relative intensity noise (RIN) and can be tuned to accomplish the off-set frequency stabilisation. 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 millimetre wave signal – used as a reference of the phase locked loop for off-set frequency stabilisation 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 photo-diode is to be applied. Therefore, these methods are very expensive.

Nevertheless, there is an increasing need for higher frequencies and thus carrier frequencies in the millimetre wave band are to be used in phased array antennas as well. The optical transmission of millimetre waves faces many obstacles. First of all, the modulation frequency of the semiconductor lasers is limited by the relaxation oscillation in the laser. The frequency of optically transmitted signals is limited at the reception side as well. Namely the sensitivity of the photo detectors is significantly reduced above 20 GHz modulation frequency. Thus the optical transmission of signals is more and more lossy when the frequency is increased into the millimetre wave region.

New optical signal generation method

The aim of this paper is to propose new methods [3] for optical generation of millimetre wave signals in phased array antennas to provide a simpler and less expensive solution.

The common basic principle of the new methods is that instead of the millimetre wave signal a low frequency reference signal is transmitted to the T/R modules and utilising this low frequency reference the millimetre wave signal is generated at the T/R module. This principle has several advantages:

- there is no need for a tuned laser or a double mode laser,
- there is no need for the off-set frequency stabilisation of two lasers,
- there is no need for the injection locking stabilisation of the two mode laser,
- there is no need for a high frequency external modulator,
- an inexpensive low frequency photo diode can be utilised,
- the chromatic dispersion effects are overcome.

However, there is a noticeable disadvantage, namely the more complex optical receiver set-up. However, this problem can easily be solved by the application of the integrated circuit technology.

This basic principle can be applied in several ways.

- The received low frequency signal is amplified and by frequency multiplication the wanted millimetre wave signal is created. This method has some drawbacks: the efficiency of the frequency multiplication is rather poor and its bandwidth is not broad enough which limits the sweeping property of the antenna.

- The received low frequency signal is used for subharmonic injection locking of the millimetre wave oscillator. As the subharmonic number is rather high the locking range of the millimetre wave signal is very small and very sensitive to changes in the bias voltages, ambient temperature, circuit parameters etc. Sweeping the millimetre wave frequency is also almost impossible in this case.

- The received low frequency signal is utilised as a reference for a phase locked loop of a millimetre wave oscillator. For this purpose the frequency of the oscillator output signal is divided down to the frequency of the reference [3], or the reference signal frequency is multiplied e.g. by a harmonic mixer into the millimetre wave region to be compared in the phase detector of the PLL [4,5]. In these cases the efficiency of the millimetre wave generation is good enough and the frequency of the generated signal can be swept in the tuning range of the millimetre wave oscillator.

Comparing the previous three realisation methods of the new principle the third method seems to be the best one. Therefore, it has been chosen for its practical implementation into a system. To improve the efficiency of this approach a harmonic oscillator has been utilised.

In the new approach a single mode laser is intensity modulated by the subharmonic reference signal. The detected signal is used to stabilise the VCO frequency by a phase locked loop. The block diagram of this system is shown in Fig. 1.

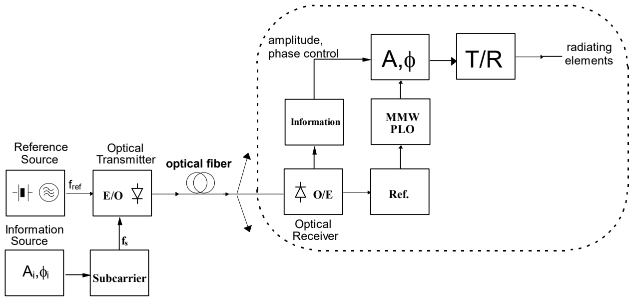

Fig. 1 The block diagram of the system

Beside the reference signal a subcarrier is used for optical transmission of an information channel. This information channel can consist of the amplitude and phase information for the control of the antenna unit.

The main task is to ensure the low noise property of the millimetre wave signal. Comparing the well-known methods and the new method it is obvious that the electronic system part producing the millimetre 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 quartz crystal oscillator with a low noise as the basic reference.

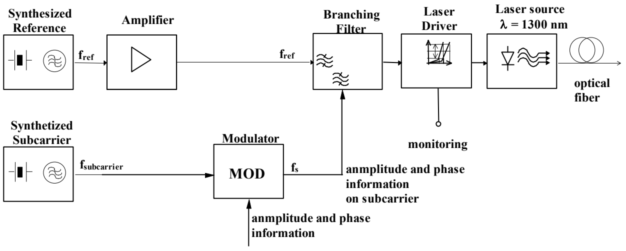

Fig. 2 The block diagram of the optical transmitter

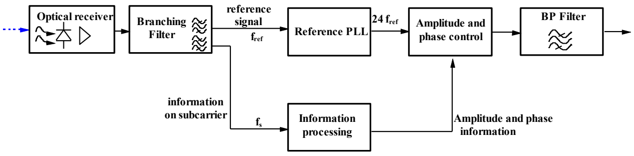

Fig. 3 The block diagram of the optical receiver

The block diagram of the optical transmitter and the optical receiver of the system are presented in Figs. 2 and 3, respectively. In the PLL unit of the receiver a voltage controlled harmonic oscillator (VCHO) serves for generating the millimetre wave signal [6,7]. The VCHO has the fundamental oscillation frequency at 8.44 GHz and its third harmonic provides the output signal. At the same time the fundamental frequency of oscillation is coupled out, divided by 8 and compared to the reference signal in a phase detector at 1.055 GHz.

Design of the harmonic oscillator

The power and the phase noise of the generated MMW signal are mainly influenced by the quality of the reference signal and the PLL loop. In a PLL loop appropriate for this application a VCHO with high harmonic level and low phase noise is required.

A conventional method to construct an oscillators with high harmonic output is the application of a relatively high power fundamental oscillator followed by a frequency multiplier. In this way an output frequency higher than 100 GHz can be achieved. Applying a dielectric resonator fundamental oscillator a better phase noise characteristic can be obtained. However, beside the complex construction the tuning range of this type of MMW sources is relatively narrow mainly due to the narrow bandwidth of a frequency multiplier.

In the new system a cheaper and simpler solution is used, a VCO with high harmonic content [8,9]. The operation of the oscillator can be investigated on a simplified configuration which consists of a non-linear amplifier ($A(g)$) and a linear feedback network ($K(\omega)=K_r(\omega)+jK_i(\omega)$) as shown in Fig. 4 [10].

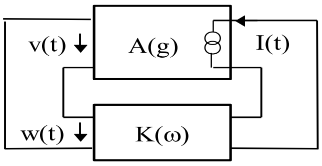

Fig. 4 Simplified model of the VCO

The non-linear characteristic of the amplifier is shown in Fig. 5. In a transistor oscillator the transconductance of the active device corresponds to the amplifier, ($A(g)$) and all other elements (transistor parasitics and external circuit elements) are involved into the feedback circuit, ($K(\omega)$).

Depending on the feedback circuit design wide tuning bandwidth (hyperabrupt tuning varactor, lower resonator Q) or good phase noise characteristic (dielectric resonator, high Q abrupt tuning varactor) can be applied.

The high level of the harmonics are generated by driving the active element of the oscillator circuit into saturation or/and below pinch-off at the positive and negative peaks of the output signal, respectively. This operation is illustrated in Fig. 5 if only the fundamental is fed back to the amplifier input. This strongly non-linear operation is achieved by applying strong feedback. The harmonic content can be optimised according to the application requirements by the proper choice of the operation point (operation class) of the active device. The operation point can be adjusted by varying the transfer function of the feedback circuit (X_1) and the gate bias voltage (V_0) of the transistor.

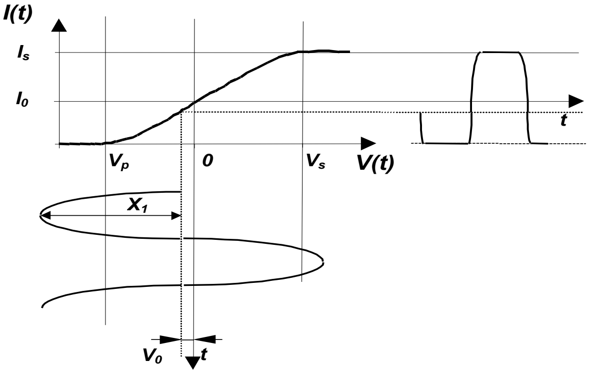

Fig. 5 Harmonic generation by the truncation of the VCO output signal

Applying the non-linear I_{DS}-V_{GS} characteristic of the used NE13783 type MESFET from NEC, Fig. 6.a and Fig. 6.b show the magnitude of the fundamental (B_1) and the third harmonic (B_3), respectively, at the output of the amplifier versus the amplitude of the input (gate) signal (X_1) and the gate bias voltage (V_0).

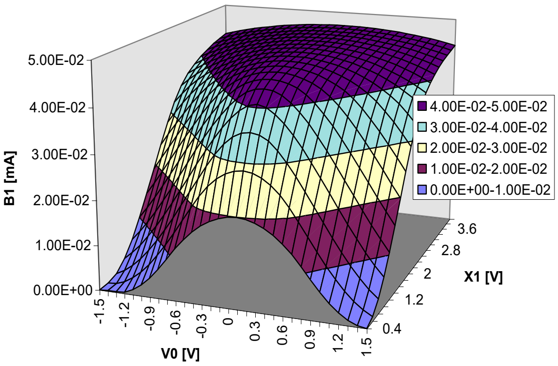

Fig. 6.a Fundamental magnitude of the VCHO

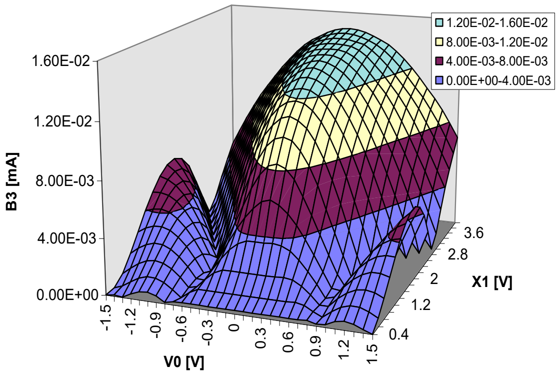

Fig. 6.b , Third harmonic magnitude of the VCHO

According to the figures the fundamental and the third harmonic are maximum if the output signal is symmetrically truncated. To achieve this operation point zero gate bias voltage was applied. The picture of the constructed oscillator comprises the branching filter to separate the fundamental and the third harmonic as shown in Fig. 7.

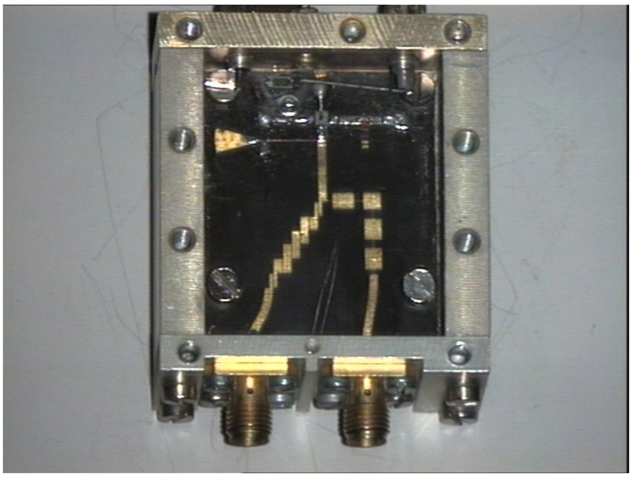

Fig.7 Picture of the realized VCHO

In Fig. 8.a and Fig. 8.b the measured frequency and power of the fundamental and the third harmonic are depicted as functions of the tuning varactor voltage, respectively. The powers of the signals were measured behind the branching filter.

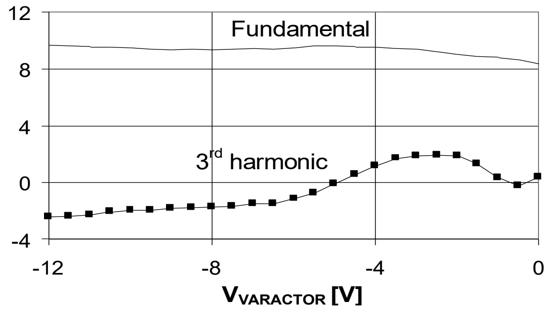

Fig. 8.a Fundamental and third harmonic power [dBm]

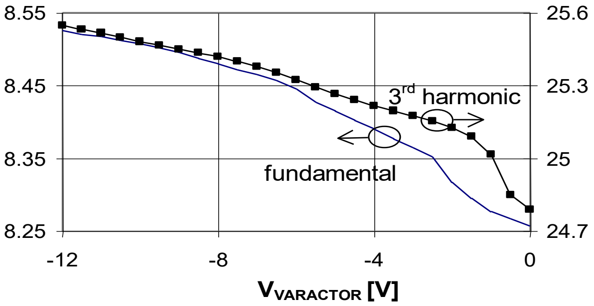

Fig. 8.b Fundamental and third harmonic frequency, [GHz]

Measurement results of the system

The optical transmitter contained a Fabry-Perot laser diode. Its optical output power was varied by direct bias current modulation. The measured frequency response is plotted in Fig. 9. The transmission is flat until 2 GHz modulation frequency.

The spectrum of the reference signal is presented in Fig. 10. As seen the shape and the noise of the reference signal (Ref. Osc.) provided by a quartz oscillator is unchanged when it is used direct electrical connection (PLL El.) or through the optical connection (PLL Opt.) to the phase locked loop.

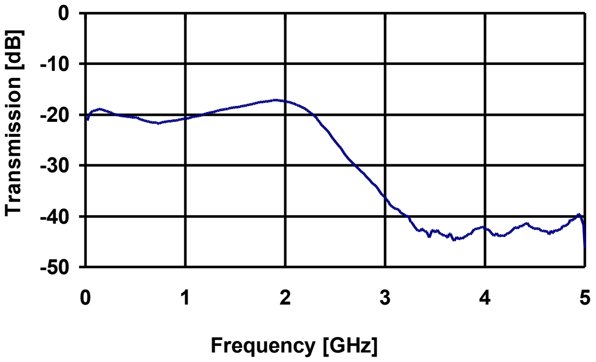

Fig. 9 The measured frequency response of the optical transmitter

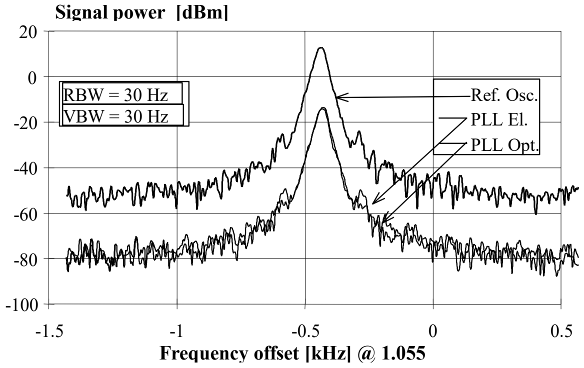

Fig. 10 Spectrum of the reference signal

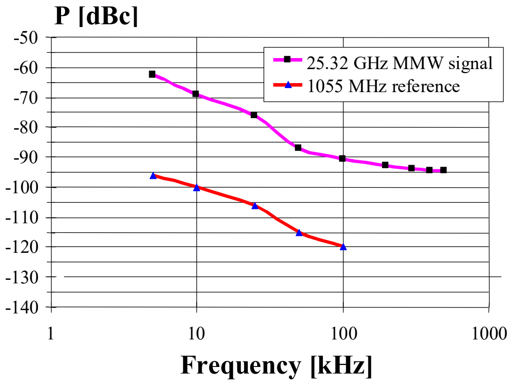

Figure 11. Phase noise of the generated MMW signal

Fig. 11 shows the phase noise of the generated millimetre wave signal along with the phase noise of the reference signal as functions of the frequency. Considering the multiplication number of 24 which means 27 dB noise increase in principle, there is no noticeable degradation in the noise level of the generated millimetre wave signal.

In Fig. 12 the phase jitter distribution of the millimetre wave signal is depicted. The average phase jitter is 2.25°. As the reference signal has a phase jitter of ≈0.09° and the multiplication number of the frequency is 24, the noise contribution of the system is negligible.

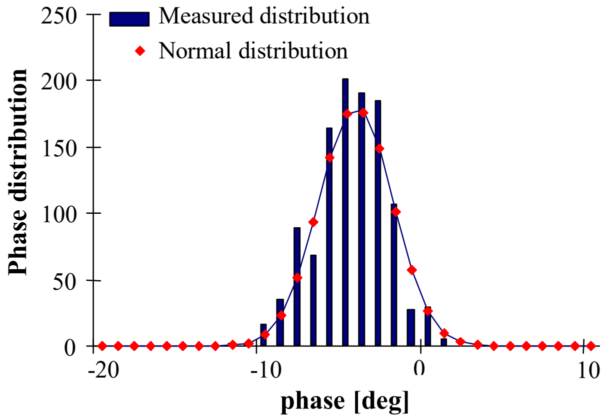

Fig. 12 Phase distribution of the generated MMW signal (σ = 2.25 deg @ 25.32 GHz)

The optical signal distribution system can feed several T/R modules as shown in Fig. 13. The main beam forming can be realised with optical phase shifters. The signals for amplitude and fine phase control are transmitted in a TDMA (time division multiple access) format to the T/R module.

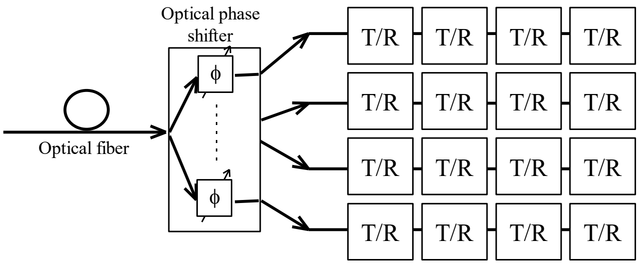

Figure 13. The optical signal distribution

The receiver side of the phased array antenna can be realised in the similar way as the transmitter part. The received signal after down conversion can be transmitted with a low cost optical link.

Conclusion

A new approach has been presented for the optical generation of millimetre waves with the intention to feed the phased array antennas of radar systems. In this approach an optically transmitted subharmonic reference signal has been used to stabilise a voltage controlled harmonic oscillator providing the millimetre wave signal. This method offers a simple and inexpensive solution.

APPENDIX

Dispersion in microwave-optical systems

The pure silica fiber has no first order dispersion around 1300 nm and it has less than 20 ps/(km•nm) dispersion at 1550 nm. Even this small value must be taken into account in microwave optical systems, where millimeter wave modulation signals have to be detected. The intensity modulation of the light having Ω frequency with a microwave modulating signal of ω frequency causes that two sidebands appear at $\Omega+\omega$ and $\Omega-\omega$. This means three separate optical signals differing in wavelength if a narrow linewidth laser is assumed. This difference can be so large, that the dispersion of the fiber makes sufficiently long delay between them. The time delay means phase shift of the representing phasors. The total electric field is the sum of the three components in the receiver and the detected signal is related to its envelope because of direct detection. Thus, the detected power depends on the phase shifts and eventually on the lengths and the dispersion of the fibre. In a certain situation the ω frequency signal can not be detected.

Fig. 14 shows the calculated transfer characteristic which is defined as

$$G(\omega) = \frac{I_{\mathrm{detected}}(\omega)}{I_{\mathrm{modulation}}(\omega)} \tag{1}$$

where I means current and the optical to electrical conversion is assumed to be ideal. In Fig.14 100 km long fibre is calculated with 9 ps/(km•nm) dispersion using 1550 nm source. In the calculations the attenuation of the fibre was neglected and the linewidth enhancement factor was assumed to be zero because of using external modulation.

This optical fibre model is not linear. At frequencies where the transfer function starts to decrease, higher order harmonics appear which must be taken into account in the system design.

Design principles can be derived for microwave-optical systems with this mathematical model. In case of baseband applications the 3 dB bandwidth of the fibre is:

$$B = \frac{\nu}{\sqrt{(8DLc+1)}} \tag{2}$$

where D is the total chromatic dispersion of the single mode fibre, c is the speed of light in vacuum, L is the length of the fibre and ν is optical frequency.

The bandwidth - fibre length product can be approximated from (2) with:

$$L \cdot B^2 = \frac{c}{8D\lambda^2}\,, \tag{3}$$

where λ is the optical wavelength.

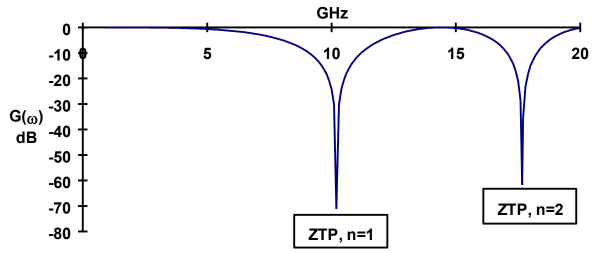

Fig. 14 Calculated transfer characteristic of a fibre at millimetre wavelengths

If this fibre approach is used instead of the low-pass Gaussian filter approach, there are several passbands over the baseband. These are situated after zero transmission points (ZTP), which are getting closer as the frequency increases. The frequency of the zero transmission points (ZTP) of the optical media can be calculated to exclude those ranges from the modulation band:

$$f = \sqrt{\frac{k}{4DLc - k}} \cdot \nu \qquad (4)$$

where k is an even integer and corresponds to the nth ZTP as k = 2n-1. Using the k number, the bandwidth - fibre length product can get a new interpretation. The start frequency and the bandwidth of the passband between the nth and (n+1) th ZTP is:

$$f = \sqrt{\frac{k}{8DLc - k}} \cdot \nu, \qquad B \cong \frac{\sqrt{k+2} - \sqrt{k}}{\sqrt{8DLc - k}} \cdot \nu, \qquad k = 4n - 1 \qquad (5)$$

Increasing the fibre length or the dispersion, the bandwidth of these passbands decreases similarly to the baseband. The bandwidth – fibre length product corresponding to the passband above the nth ZTP:

$$L \cdot B^2 \cong \frac{k + 1 - \sqrt{k^2 + 2k}}{4Dc} \cdot \nu^2 \qquad (6)$$

This value is always less than that in the baseband, but the fibre capacity can be increased over its usual baseband limit by using these frequency ranges.

The cromatic dispersion can be overcome with dispersion shifted fibre, but this solution is too expensive.

Acknowledgement

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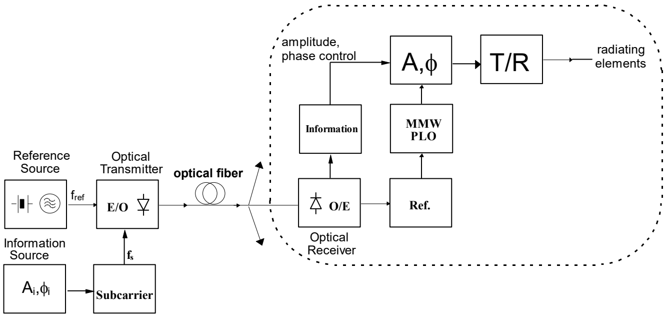


Figure.1 The block diagram of the system

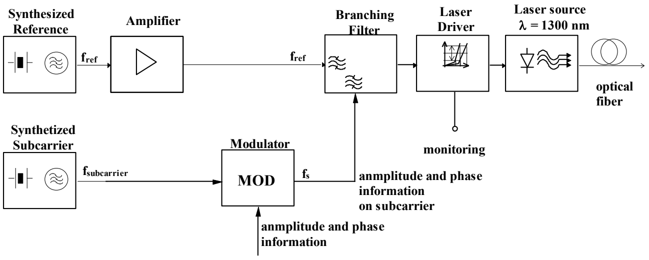


Figure.2 The block diagram of the optical transmitter

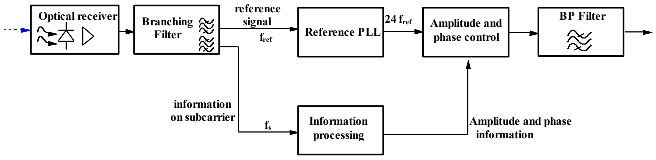


Figure.3 The block diagram of the optical receiver

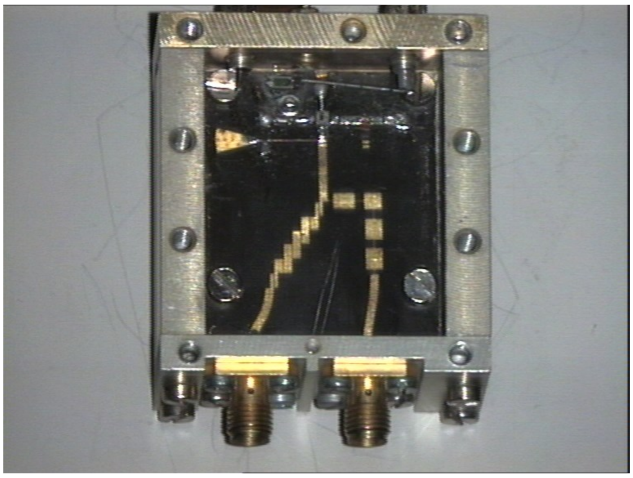


Figure.7 Picture of the realized VCHO

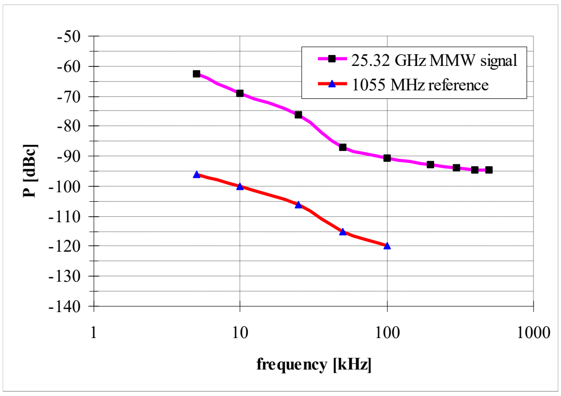


Figure 9. Phase noise of the generated MMW signal

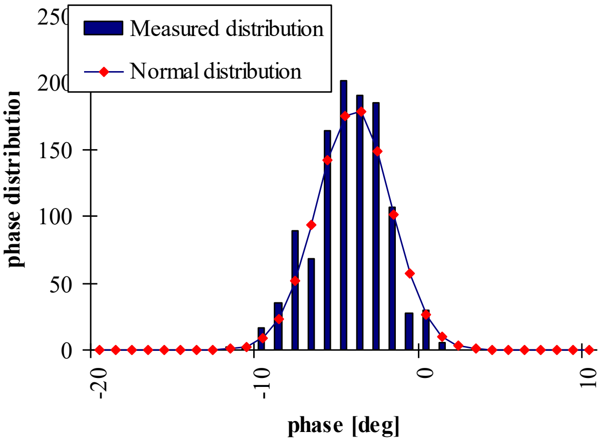


Figure 11. Phase distribution of the generated MMW signal

(s = 2.25 deg @ 25.32 GHz)

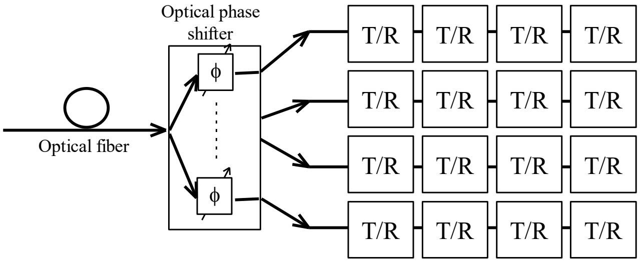


Figure 12. The optical signal distribution

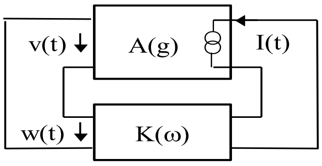


Fig. 4, Simplified model of the VCO

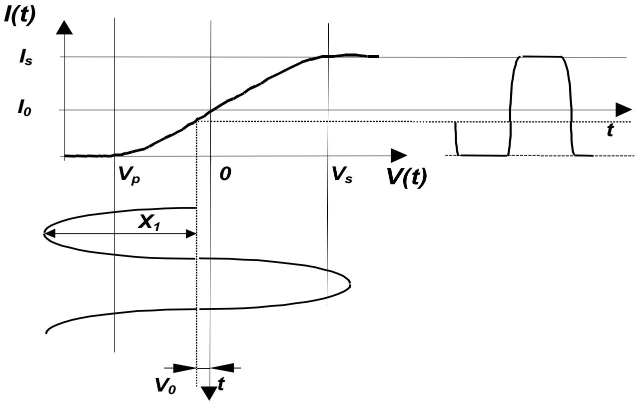


Fig. 5, Harmonic generation by the truncation of the VCO output signal

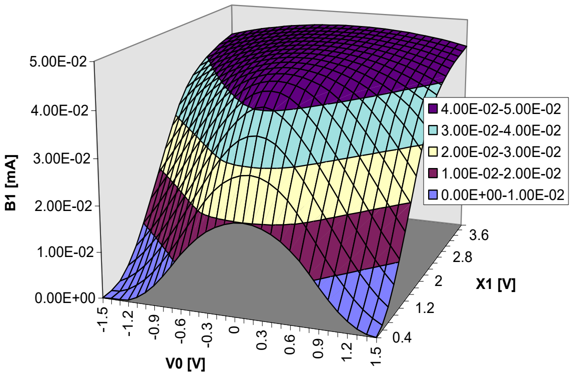


Fig. 6.a , Fundamental magnitude

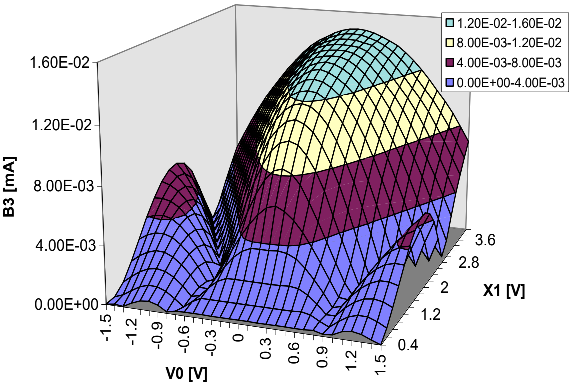
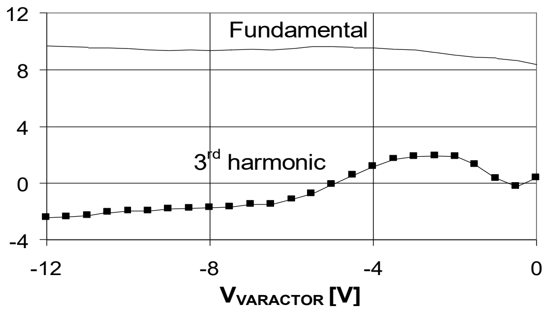


Fig. 6.b , 3rd harmonic magnitude



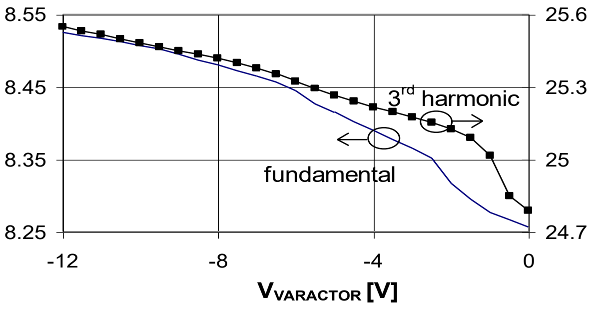


Fig. 8.b, Fundamental and 3rd harmonic freq. [GHz]

Fig. 8.a, Fundamental and 3rd harmonic power [dBm]

Fig. 8.b, Fundamental and 3rd harmonic freq. [GHz]

This way the frequency difference between the two laser beams is in the millimetre wave region. These two beams are transmitted via a filter to the T/R module where the millimetre wave signal is regained by optical detection. In some cases the frequency of the millimetre wave signal has to be swept. That can be achieved by using a swept frequency synthesiser as a reference for the off-set stabilisation of the two lasers. However, sweeping the frequency of a stable and low noise synthesiser in the millimetre wave region is a rather difficult task.