BER performance comparison between an active Mach-Zehnder modulator and passive Mach-Zehnder interferometer for conversion of microwave subcarriers of BPSK signals

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Abstract:

BER performance of a classical external optical Mach-Zehnder modulator and of a passive all-optical integrated device (unbalanced Mach-Zehnder interferometer) are measured and analysed theoretically. This analysis show better results for passive all-optical device than for external modulator in case of high enhancement factor of the laser diode.

Index terms: Optical fiber communication, integrated optical device, external optical modulator, optical microwave mixing, bit error rate.

I. Introduction

In the new hybrid MW/optical digital transmission systems, the optical domain is not only used to transmit MW signals but provides also signal processing functions as optical MW frequency mixing. This very useful signal processing function allows changing the carrier frequency of digital signals for various applications in telecommunications or radar domains [1]. Here, performance of an external optical Mach-Zehnder modulator (EOM) and of a passive all-optical device (unbalanced Mach-Zehnder interferometer UMZ) in a frequency modulated (FM) fiber-optic link are compared. Comparison is carried out through a theoretical approach and BER measurements function of the input optical power. Although the technique of up and down conversion of MW subcarriers has been published [2], the BER performance and the comparison between passive UMZ and EOM is conducted for the first time.

II. Theoretical approach of optical microwave mixing for EOM and UMZ

Optical microwave mixing is always generated by exploiting a nonlinearity. In both cases presented here, the nonlinearity is the sinusoidal function described by the output optical power.

II.1 Optical microwave mixing with an EOM

The optical power of the EOM is a sinusoidal function of bias voltage. Let us consider two MW CW RF and LO signals, respectively at frequencies f_{RF} and $f_{LO,}$ and with magnitudes V_{RF} and V_{LO}. They are added at the electrical input of the EOM. When the EOM operates at maximum or minimum of transmission [3], the optical field at its output is given by :

$$E(t) = E_o \exp(j2\pi f_{opt} t)\left(1+\exp\left(j\frac{\pi V_o}{V_\pi}+j\frac{\pi V_{RF}}{V_\pi}\cos(2\pi f_{RF}t)+j\frac{\pi V_{LO}}{V_\pi}\cos(2\pi f_{LO}t)\right)\right) \qquad (1)$$

where E_o is the amplitude of optical field, V_0 is the bias voltage of the EOM, f_{opt} the optical frequency and V_π is the EOM half wave voltage.

So the power at the output of the EOM can be written as:

$$P_{out} = \frac{T_i P_0}{2}\left[1 \pm \cos\left(\frac{\pi V_{RF}}{V_\pi}\cos(2\pi f_{RF}t)+\frac{\pi V_{LO}}{V_\pi}\cos(2\pi f_{LO}t)\right)\right] \qquad (2)$$

where T_i is the optical insertion loss of the modulator, P_0 is the optical power at its input. After Bessel function expansion and assuming that the power of the LO signal is chosen in order to maximise the mixing power and that the power of the RF signal is low, the power detected at the mixing frequencies after quadratic photodetection can be written as :

$$P_{mix} \approx R_{PD}(T_i P_0 m_{RF} 0.58)^2 \qquad (3)$$

where R_{PD} is a term due to optical/electrical conversion and m_{RF} is the optical intensity modulation index that would be induced with the modulator biased at quadrature and modulated only by the RF signal.

II.2 Optical microwave mixing with a passive UMZ

In the second case, mixing is generated by an alternative method detailed in [2]. The RF and LO signals directly modulate a LD which is followed by a passive UMZ. Direct modulation of the LD induces both intensity modulation (IM) and FM of the light. The optical power at the output of the interferometer is also a sinusoidal function of the optical frequency. Therefore, this configuration must intuitively have the same behaviour as in the last section.

For better understanding, we can neglect IM. Simulations show that its effect does not change significantly the total response. Indeed, if we neglect the IM, the optical field emitted by the LD can be written as :

$$E(t) \approx E_0 \exp j(2\pi f_{opt} t) \exp j\left(\beta_{RF} \sin\left(2\pi f_{RF1} t\right) + \beta_{LO} \sin\left(2\pi f_{LO} t\right)\right) \quad (4)$$

where β_{RF} and β_{LO} are the frequency modulation index at frequency f_{RF} and f_{LO}.

This optical field contains all the harmonics and intermodulation products of the input signals. But, the interferometer acts as a linear filter on this optical field and can consequently suppress some spectral components. With two conditions, stated hereafter, the optical power at the output of the UMZ, calculated from the coherent beating of the optical field, has a completely analogous form as in the previous case :

$$P_{out} = \frac{T_i P_0}{2} \left[1 \pm \cos\left(2\beta_{RF} \cos\left(2\pi f_{RF} t\right) + 2\beta_{LO} \cos\left(2\pi f_{LO} t\right)\right)\right] \quad (5)$$

where T_i is the insertion loss of the interferometer including the coupling and the propagation loss.

The first condition concerns specific relations between input frequencies values and the free spectral range of the interferometer (FSR) :

$$f_{RF} = (2k+1)\frac{FSR}{2},\ k \in \mathrm{N} \ \text{and}\ f_{LO} = (2k'+1)\frac{FSR}{2},\ k' \in \mathrm{N} \quad (6)$$

Deeper analysis shows that a tolerance of 3 dB on the variation of P_{mix} implies a variation of the input frequencies in a bandwidth equal to FSR/2.

The second condition concerns the interference regime which, as in the first case with the external modulator, has to be maximum or minimum :

$$\cos\left(\frac{2pf_{opt}}{FSR}\right) = \pm 1 \qquad (7)$$

This is easily realisable with an integrated optical component [2]. Supposing as previously that the power of the LO signal is chosen in order to maximise the mixing power and that the power of the RF signal is low, the power detected at the mixing frequencies after quadratic photodetection can be written as :

$$P_{mix} \approx R_{PD}\left(T_i P_0 m_{RF} a\, 0.58\right)^2 \qquad (8)$$

where R_{PD} is the same term due to optical/electrical conversion and m_{RF} is the optical intensity modulation index which would be measured at the output of the LD, α is the linewidth enhancement factor of the LD. Logically, the greater α is, meaning the more efficient the FM response due to the chirp of the LD is, the more efficient the mixing response is.

II.3 Dispersion tolerance

It is well known that chromatic dispersion can lead to drastic penalty in detected signal power. This effect depends on the characteristics of the spectrum of the propagated optical field. Even if the optical intensity for both systems is the same at minimum or maximum of transmission, the nature of the optical field is completely different. According to the expression (1), fundamental spectral lines $f_{opt} \pm f_{LO}$ and $f_{opt} \pm f_{RF}$ are higher at the output of the EOM, the optical carrier is almost suppressed at minimum of transmission, and dominant at maximum of transmission. According to the expression (4) multiplied by the transfer function of the UMZ, at minimum of transmission, only spectrum lines expressed as $f_{opt} \pm (2k+1)FSR/2 \quad k \in N$ remain in the optical spectrum. At maximum of transmission this time, only spectrum lines expressed as $f_{opt} \pm k' FSR/2 \quad k' \in N$ are present in the optical spectrum at the output of the UMZ.

These spectral components will concurrently beat on PD to generate MW mixing. The significant difference between optical fields for both systems implies a great difference in terms of dispersion tolerance that can only predicted with numerical simulations.

Finally, the comparison of the two methods working in similar conditions, with same intensity modulation index m_{RF} and with same insertion loss T_i (in fact, the insertion loss with UMZ could easily be even better than the insertion loss of the EOM) shows a gain factor equal to α^2 in the case of the UMZ. In long optical fiber systems, numerical simulations are needed to evaluate dispersion tolerance.

III. Application for conversion of subcarriers of BPSK digital signals

III. 1 Conversion of subcarriers of digital signals using an EOM

Optical MW mixing is investigated with a DFB laser diode (LD) emitting at 1550 nm and an EOM modulated by a CW signal at f_{LO} =1.55 GHz (P_{OL}=5 dBm) and a 100 Mbit/s BPSK digital signal at f_{RF}=4.45 GHz (P_{RF}=0 dBm). A DC voltage is also applied to use the EOM in a non-linear regime (inset of Fig. 1). Optical power is detected at the output of the EOM by a photodetector (PD). As shown on Fig. 1, digital signal is up and down-converted around $f_{mix+}=f_{RF}+f_{LO}$=6 GHz and $f_{mix-}=f_{RF}-f_{LO}$=3 GHz at the output of the EOM. Rejections of f_{RF} and f_{LO} are greater than 15 dB.

III. 2 Conversion of subcarriers of digital signals using a passive UMZ

The previous LD is used in the linear regime and is directly modulated by the same MW and digital signals as described above. This LD has a linewidth enhancement factor of 4.5. Optical power is coupled into an optical fiber, then injected into the UMZ and detected at its output by the

PD (inset of Fig. 2). The UMZ is integrated on a glass substrate by Tl^+/Na^+ ion exchange and has a FSR equal to 3 GHz. The control of the interference regime is easily realized by fixing the temperature of the LD and of the component (with a Peltier element), and by varying the bias of the LD to control the emitted wavelength. A variation of interference regime from a maximum to the next one is induced by variation of temperature equal to 1.5°C for the UMZ, 0.25°C for the LD or by a variation of the LD bias equal to 2 mA. As shown on Fig. 2, digital signal is up and down-converted around $f_{mix+}=f_{RF}+f_{LO}=6$ GHz and $f_{mix-}=f_{RF}-f_{LO}=3$ GHz at the output of the UMZ. In the same way as previously, rejections of the input signals are greater than 15 dB [4].

III.3 Comparison of BER performance

BER measurements using EOM and passive UMZ have been carried out with the same electrical part to make a valid comparison. IM index and insertion loss can be easily measured for both systems. They have also to be taken into account to compare BER measurements function of optical input power for the two systems. As expected, passive UMZ gives sensibly better BER values for the same optical input power and for equal intensity modulation index and no insertion loss (Fig. 3). For a 10^{-9} BER value, input optical power must be –7.5 dBm for EOM whereas it must be only –13 dBm for UMZ considering equal intensity modulation index and no insertion loss. Average optical power difference between the two BER curves is about 6 dB_{opt} that corresponds to $10\log(\alpha)=6.5$ dB_{opt}. So, optical MW mixing power with passive UMZ is optimized by a α^2 factor compared to EOM, that corresponds electrically to about 12 dB.

IV. Conclusion

A new method for MW conversion of subarriers of digital signals using a low cost and compact UMZ device have shown low BER measurements. As expected in theory, these results are better than BER measurements with EOM when laser diode has enhancement factor higher than 1. For using in long distance optical fiber transmission systems, numerical simulations are needed to evaluate the effect of chromatic dispersion for each particular case.

References

[1] J. Mari, F. Ramos, V. Polo, J. M. Fuster, J. L. Corral, *Millimeter-Wave Signal Generation and Harmonic Upconversion Through PM-IM Conversion in Chirped Fiber Gratings*, Fiber and Integrated Optics, Vol. 19, 2000,pp. 187-198.

[2] G. Maury, A. Hilt, T. Berceli, B. Cabon, and A. Vilcot, *Microwave-frequency conversion methods by optical interferometer and photodiode*, IEEE Trans. on Microwave Theory and Techniques, vol. 45, no. 8,pp. 1481-1485,1997.

[3] T. Young, J. Conradi, W. R. Tinga, *Generation and Transmission of FM and p/4 DQPSK Signals at Microwave Frequencies Using Harmonic Generation and Optoelectronic Mixing in Mach-Zehnder Modulators*, Transactions on Microwave Theory and Techniques, Vol. 44, No.3, March 1996, pp.446-453.

[4] Y. Le Guennec , B. Cabon , G. Maury, *Conversions of the Microwave Subcarriers of Digital Signals in Optical Links*, LEOS Conference, San Diego, USA, November 2001.

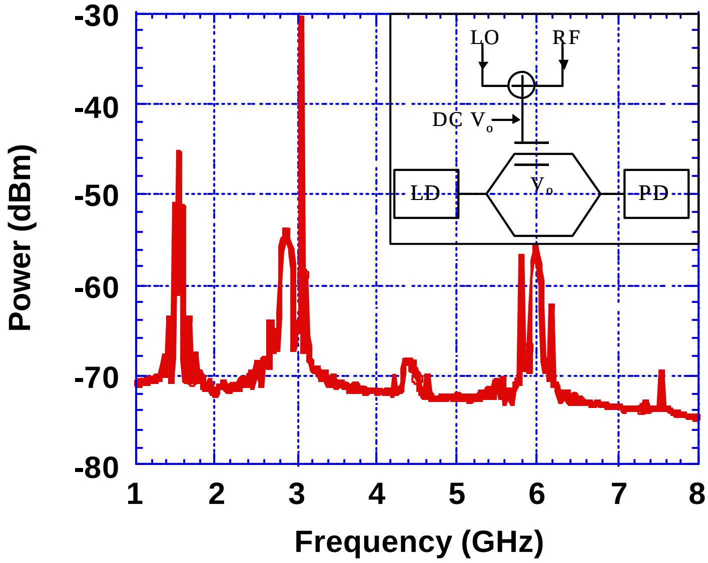

Fig. 1. Spectrum at the output of the EOM

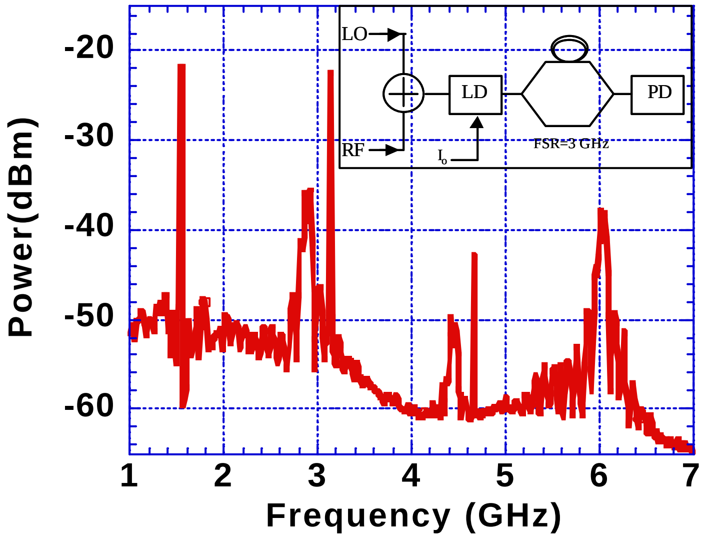

Fig. 2. Spectrum at the output of the UMZ

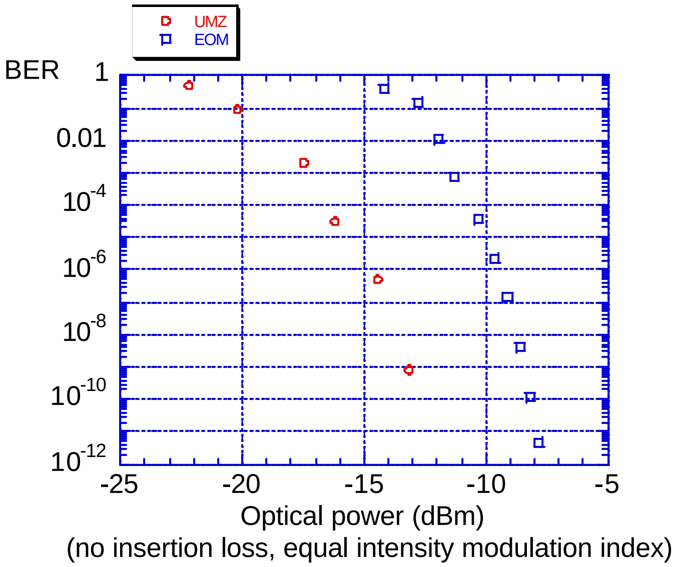

Fig. 3. BER function of the input optical power (dBm)