Improvement of dispersion resistance in analog radio-on-fiber upconversion links

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Abstract

Dispersion fiber sensitivity in optical microwave upconversion links is investigated. Simulations are carried out to calculate output optical spectra and to evaluate mixing power as a function of fiber length for different upconversion systems using Dual Drive/standard Mach Zehnder Modulators or an unbalanced Mach Zehnder interferometer (UMZ). The latter solution prevents complete cancellation of mixing power because of the asymmetric double sideband optical spectrum detected at the output of the UMZ. It is shown that an optimum value of the linewidth enhancement factor of the laser diode can be found to minimize degradations of the mixing power along the fiber.

Index Terms

Optical fiber communications, optical fiber dispersion, analog upconversion, optical microwave mixing, Mach Zehnder modulator, passive unbalanced interferometer.

I. INTRODUCTION

External Mach Zehnder modulators (MZM) are widely used in conventional optical intensity modulation (IM). For example, the optical carrier can be modulated in the RF frequency range by a local oscillator (LO) signal to generate an optical field that includes the optical carrier and two modulation sidebands (it refers to the so called Double Sideband (DSB) modulation). If the signal is transmitted over the fiber, chromatic dispersion causes each sideband of the continuous wave (CW) modulation signal to have a different phase shift depending on the length of the fiber, dispersion fiber parameter and LO frequency modulation. At the optical receiver, each sideband beats with the optical carrier and the two beat signals ideally interfere constructively. But, when the phase shift reaches π because of dispersion group delays, the two beat signals cancel each other which results in a power degradation of the LO signal. The higher the LO frequency is, the shorter the fiber length for LO power cancellation is. Chromatic dispersion can be almost totally overcome with Single Sideband (SSB) modulation using a Dual Drive Mach-Zehnder Modulator (DD-MZM) biased at quadrature [1]. One of the two optical sidebands of the CW modulated signal is simply suppressed and total cancellation of LO power is no longer possible.

MZM are also often used to generate up and down frequency conversion of microwave (MW) signals, because they avoid insertion loss due to E/O and O/E conversions [2]. Moreover upconversion allows to generate higher frequency than that which could be obtained by simple direct modulation of a laser diode. Many applications have been found in the fields of defence radar and telecom systems in which intermediate RF frequencies must be generated from an LO signal [3]. These conventional solutions using MZM for generation of MW mixing are expensive and we have reported yet a solution based on a quite unexpensive UMZ [4]. In this solution, which uses a passive component, a conversion gain can be obtained in addition, which represents a great advantage over traditional methods that use active MZM. As for IM, the generation of up-converted MW signals at high frequency suffer also from periodic degradation of the detected upconverted signal power after propagation along a dispersive fiber.

In this article, the most widely used techniques for optical MW mixing of CW signals are exposed and analyzed in terms of dispersion resistance. The use of MZM or DD-MZM biased at quadrature as upconverters of intermediate frequency (IF) modulation has been yet analyzed theoretically [5]. Dispersion resistance of these solutions is here compared to an MZM operating in a non linear regime when both MW signals (IF and LO) are applied to the modulator. Our original method using the UMZ with direct frequency modulation (FM) of a DFB laser diode (LD) converted into IM is studied for the first time in terms of dispersion resistance. Direct analysis of the output optical spectra of the different MW mixing devices is made to discuss dispersion sensitivity. Simulations of mixing power as a function of fiber length are carried out for all these optical mixing systems (DD-MZM, MZM and UMZ). It is shown that the common solutions have more sensitivity to fiber chromatic dispersion than the solution based on UMZ.

This paper is organized as follows. In section II, the general expressions of optical field spectra at the output of optical mixing systems using MZM, DD-MZM are revised and compared in terms of dispersion tolerance. Simulation method and results are presented. In section III, the use of UMZ is explained and simulation results are compared to conventional solutions using MZM or DD-MZM. Finally, optimum conditions to use UMZ are discussed and a study of the influence of the linewidth enhancement factor α of the laser diode on the degradation of mixing power is carried out.

II. MZM AND DD-MZM AS UPCONVERTERS

Dispersion sensitivity is simulated here for a fiber dispersion parameter D=17 ps/km/nm at the optical wavelength λ_{opt}=1.55 µm. Calculations are made in the Fourier domain using the expression of the optical transfer function $H_{fib}(f)$ of the fiber :

$$H_{fib}(f)=\exp\left[j\frac{\pi D L \lambda_{opt}^2 \left(f-f_{opt}\right)^2}{c}\right] \quad (1)$$

where f is the optical carrier frequency when the LD is modulated by a LO at frequency f_{LO}, f_{opt} is the optical carrier frequency emitted by the unmodulated LD, L is the length of the fiber, c is the speed of light in vacuum. The spectrum of the optical field $E_{out}(f)$ is then obtained by multiplying $H_{fib}(f)$ with the Fourier Transform of the optical field E(t) at the output of the mixing device [2]:

$$E_{out}(f)=H_{fib}(f)\times FT(E(t)) \quad (2)$$

Finally, after an Inverse Fourier Transform of $E_{out}(f)$, the mixing power P_{mix} at the output of the fiber is obtained by analyzing the spectrum $I_{out}(f)$ after quadratic photodetection :

$$I_{out}(f)=FT(E_{out}(t)\times E_{out}^{*}(t)) \quad (3)$$

a) Upconversion with IF intensity modulation on a first MZM + LO modulation applied to a second MZM or DD-MZM (MZM+MZM or MZM+DD-MZM)

A DD-MZM converter is biased at each arm of the interferometer as shown on Fig. 1. General expressions for applied voltages $V_1(t)$ and $V_2(t)$ are:

$$\begin{cases} V_1(t) = V_{DC1} + V_{LO}\sin(2\pi f_{LO}t + \phi_{LO1}) \\ V_2(t) = V_{DC2} + V_{LO}\sin(2\pi f_{LO}t + \phi_{LO2}) \end{cases} \quad (4)$$

V_{DCi} is a continuous bias voltage and V_{LO} is the amplitude of a CW local oscillator signal at frequency f_{LO}. A phase shift between electrodes of $|\phi_{LO1}-\phi_{LO2}|=\pi/2$ is applied to use the DD-MZM as a SSB up-converter. Standard MZM is simply a particular case of DD-MZM where $|\phi_{LO1}-\phi_{LO2}|=\pi$ (DSB upconversion) [5].

The first stage of IF modulation is realized with an ideal MZM modulator biased in linear regime. This modulation is assumed to be ideal with a low intensity modulation index $m_{IF}<<1$. An LO linear modulation is applied to the second stage of the cascaded upconversion device. Upconversion technique using 2 cascaded MZM will be called MZM+MZM whereas upconversion technique using MZM cascaded with DD-MZM will be called MZM+DD-MZM. Optical field at the output of the upconversion device MZM+MZM or MZM+DD-MZM can be written as:

$$E(t) = \frac{E_{in}}{2}\left[1+\frac{m_{IF}}{2}\cos(2\pi f_{IF}t+\phi_{IF})\right]\times\left(\exp\left[j\frac{\pi V_1(t)}{V_\pi}\right]+\exp\left[j\frac{\pi V_2(t)}{V_\pi}\right]\right)\exp\left[j2\pi f_{opt}t\right] \quad (5)$$

where E_{in} is the amplitude of the optical field delivered at the output of the LD, $\omega_{IF}=2\pi f_{IF}$, V_π is the switching voltage of the MZM. Conversion of the IF signal frequency into $f_{IF}\pm f_{LO}$ is only possible at quadrature for MZM+MZM or DD-MZM+MZM. That implies $|V_{DC1}-V_{DC2}|=V_\pi/2$ for both configurations. Frequencies of f_{IF}=1.55 GHz and f_{LO}=4.45 GHz and IM indexes are m_{IF}=0.02 et m_{LO}=0.4 were used. With these frequency values, $2.f_{IF}$=3.1 GHz can be easily separated from $f_{LO}-f_{IF}$=2.9 GHz, and the expected up-converted frequency is f_{mix}=6 GHz. Simulated optical field spectra at the output of MZM+MZM and MZM+DD-MZM are plotted respectively on Fig. 2 and Fig. 3. A symmetric optical field around f_{opt} is observed only in the case of MZM+MZM.

Fig. 4 represents upconversion mixing power at 6 GHz for MZM+MZM configuration compared to MZM+DD-MZM. For the MZM+MZM configuration, first cancellation of the mixing power at L=137 km comes from the beatings at the optical receiver of optical field components which frequency difference equals 6 GHz and which are out of phase (Fig. 2).

i) Beating at the optical receiver of f_{opt} (numbered (1) on Fig. 2) with f_{opt}-6 GHz (2) written f_{opt} (1) / f_{opt} -6 GHz (2) out of phase with f_{opt} (1) / f_{opt}+6 GHz (3)

ii) f_{opt}-4.45 GHz (4) / f_{opt} +1.55 GHz (5) out of phase with f_{opt}-1.55 GHz (6) / f_{opt}+4.45 GHz (7)

iii) f_{opt}-8.9 GHz (8) / f_{opt}-2.9 GHz (9) out of phase with f_{opt}+2.9 GHz (10) / f_{opt}+8.9 GHz (11)

The first cancellation does not occur with MZM+DD-MZM configuration because the symmetry that exists in each beating term in i) ii) and iii) has disappeared in the spectrum of E(t) as shown on Fig. 3. Second cancellation occurs at 395 km for MZM+MZM and MZM+DD-MZM configurations and is caused by the cancellation of the three beating terms together, f_{opt} (1) / f_{opt}-6 GHz (2) with f_{opt}-4.45 GHz (4) / f_{opt}+1.55 GHz (5) and with f_{opt}-8.9 GHz (8) / f_{opt}-2.9 GHz (9).

b) Upconversion with both IF and LO signals applied simultaneously to a single MZM in non linear regime (MZM case)

In this configuration expressions of V_1(t) and V_2(t) are given by :

$$\begin{cases} V_1(t) = V_{DC1} + V_{LO}\sin(2\pi f_{LO}t + \phi_{LO1}) + V_{IF}\sin(2\pi f_{IF}t + \phi_{IF1}) \\ V_2(t) = V_{DC2} + V_{LO}\sin(2\pi f_{LO}t + \phi_{LO2}) + V_{IF}\sin(2\pi f_{IF}t + \phi_{IF2}) \end{cases} \quad (6)$$

The external MZM operates as a standard modulator $|\phi_{LO1}-\phi_{LO2}|=\pi$ and $|\phi_{IF1}-\phi_{IF2}|=\pi$.
The optical field at the output of MZM is expressed by:

$$E(t) = \frac{E_{in}}{2}\left(\exp\left[j\frac{\pi V_1(t)}{V_\pi}\right] + \exp\left[j\frac{\pi V_2(t)}{V_\pi}\right]\right)\exp\left[j2\pi f_{opt}t\right] \quad (7)$$

Conversion of the frequency f_{IF} into $f_{IF}\pm f_{LO}$ is only possible when the MZM operates in the non linear regime (MInimum (MITB) or MAximum (MATB) Transmission Bias point) [5]. When $|V_{DC1}-V_{DC2}|=0$, MZM operates at MATB and when $|V_{DC1}-V_{DC2}|=V_\pi$, MZM operates at MITB. Definitions of MATB and MITB are given in Fig. 5.

The frequency values and IM indexes are the same as previously used. Optical field spectra at the output of MZM modulated by IF and LO signals show that only f_{IF} and f_{OL} harmonics and intermodulation products of even order are present in the spectrum at MATB whereas only fundamental frequencies remain in the spectrum at MITB (Fig. 6.a and 6.b). Simulation results of Fig. 7 show that first cancellation of mixing power at 6 GHz is obtained with longer fiber length for MITB than for MATB because of the wider spectrum in the case of MATB. As extreme frequencies are further each other in MATB symmetric spectrum, phase shift between beating terms will increase more rapidly with fiber length.

As shown on Fig. 7, resistance to dispersion is improved with MZM when a narrow DSB symmetric optical spectrum is obtained (MITB case). If we now compare Fig. 4 and 7, it can be derived that better performance is obtained with an asymmetric output optical spectrum using MZM+DD-MZM technique. First mixing power cancellation occurs at L=395 km for MZM+DD-MZM against L=137 km for MZM+MZM and L=220 km for MZM. Only one cancellation occurs for MZM+DD-MZM technique for a 800 km fiber link. In the next section, we demonstrate further improvements of resistance to dispersion using an UMZ as an upconverter because this device exhibits an asymmetric DSB output optical spectrum.

III.UMZ AS UPCONVERTER

Principle of optical MW mixing with UMZ has been exposed in previous articles for analog up and down conversion [4] and for conversion of MW subcarriers of digital signals [6]. This principle is recalled briefly hereafter. The laser diode (LD) is directly modulated by two signals IF and LO. In this paper, we consider an ideal LD linearly intensity modulated:

$$\begin{aligned} E_{LD}(t) = \frac{E_{in}}{2}\sqrt{(1+m_{IF}\cos(2\pi f_{IF}t+\phi_{IF})+m_{LO}\cos(2\pi f_{LO}t+\phi_{LO})} \\ \cdot\exp\left[j\beta_{IF}\sin(2\pi f_{IF}t+\phi_{IF})+j\beta_{LO}\sin(2\pi f_{LO}t+\phi_{LO})\right].\exp\left[j2\pi f_{opt}t\right] \end{aligned} \quad (8)$$

where β_{IF} and β_{OL} are the frequency modulation index for respectively IF and LO signals. The optical field at the output of the LD $E_{LD}(t)$ (9) holds terms of IM and FM. The LD has typical parameter values: an input impedance of 50 Ω, a linewidth enhancement factor (α) of 5, a threshold current of 25 mA, a biasing current of 50 mA and an emitting power of 1.6 mW. The light at the output of the LD is coupled into a glass substrate integrated UMZ as shown on Fig. 8. Optical MW mixing is obtained converting FM into IM through the UMZ. The optical transfer function of the UMZ $H_{UMZ}(f)$ depends on the free spectral range (FSR) of the interferometer:

$$H_{UMZ}(f) = (1+\exp j[\frac{2\pi f}{FSR}]) \quad (9)$$

The interference regime is fixed by the choice of the optical frequency f_{opt} depending on the bias of the LD. The spectrum of the optical field at the output of the UMZ E(f) is then expressed by :

$$E(f) = H_{UMZ}(f)\times FT(E_{LD}(t)) \quad (10)$$

Optimum optical MW mixing is obtained working at MATB (Ψ=0) or MITB (Ψ=π) as for MZM but with frequencies respecting condition given by :

$$\begin{cases} f_{IF} = (2k+1)\frac{FSR}{2}, \ k\in\mathrm{N} \\ f_{LO} = (2k'+1)\frac{FSR}{2}, \ k'\in\mathrm{N} \end{cases} \quad (11)$$

This condition is linked to the fact that the UMZ acts as a linear filter [5]. As FSR is equal to 3 GHz, the input signal frequencies f_{IF}=1.55 GHz and f_{LO}=4.45 GHz are really close to the ideal values 1.5 GHz and 4.5 GHz, these values avoid confusion between intermodulation products. IM indexes are m_{IF}=0.02 and m_{LO}=0.4 as previously.

Fig 9.b and 10.b show simulated optical field spectra at the output of UMZ in the case of MATB and MITB that are in good agreement with measurements (Fig 9.a and Fig. 10.a respectively). Simulation results on Fig. 11 compare dispersion effect with the UMZ and with the MZM (Fig. 7). It shows that minima of mixing power are at exactly the same fiber lengths as for MZM but no deep cancellations occur in the case of UMZ. This great advantage comes from the fact that the UMZ optical field spectra (Fig. 9 and 10) are really similar to MZM spectra (Fig. 6) but with asymmetric amplitudes of spectral lines due to the combined FM and IM of the light at the output of the LD. DSB asymmetric spectra make impossible complete cancellation of the sum of all the beating terms. As for the MZM case, first minimum at MITB occurs after a longer fiber length than at MATB but the minimum is deeper in the MITB case. Then, MATB with the UMZ can be considered as the more resistant case. This better resistance to dispersion is obtained because more asymmetrical spectral lines beat to generate the 6 GHz upconverted signal.

Now let us consider the most resistant case only: MATB. Fig. 12 shows simulations of the influence of the linewidth enhancement factor α on maximum fluctuations of the mixing power (P_{max}-P_{min}) defined on Fig. 11 for different values of input frequencies (f_{IF}=1.55 GHz, f_{LO}=4.45 GHz), (f_{IF}=0.8 GHz, f_{LO}=5.2 GHz) and (f_{IF}=0.2 GHz, f_{LO}=5.8 GHz). All these frequency values lead to the same up-converted frequency of 6 GHz. The linewidth enhancement factor of DFB laser diodes is typically in the range 0.5 to 10 [7]. Fig. 12 shows minimal value for (P_{max}-P_{min}) for a optimum value of the linewidth enhancement factor α of about 2.7 in the case of quasi ideal frequency values (f_{IF}=1.55 GHz, f_{LO}=4.45 GHz). In this condition, it was demonstrated [8] that we have a mixing gain of about $10\times\log(\alpha^2)$=8.6 dB whereas, in the same conditions of operation, the MZM and DD-MZM solutions would exhibit conversion losses. We notice here that another great interest is that there are very low fluctuations (2.5 dB) of mixing power along the fiber. These results are major advantages compared to classical techniques discussed in section II. When frequencies do not respect (11) fluctuations of P_{mix} increase dramatically as fast as the frequency values differ from ideal values. For example when f_{IF}=0.2 GHz and f_{LO}=5.8 GHz fluctuations of P_{mix} reach more than 18 dB.

IV. CONCLUSION

We have compared 3 optical MW upconversion techniques using MZM, DD-MZM or UMZ and we have shown the impact of dispersion on the mixing power. SSB upconversion technique with DD-MZM and first stage intensity modulation leads to asymmetric optical field spectrum. This effect causes a longer fiber length for first mixing power cancellation for the MZM+DD-MZM technique than for MZM+MZM technique. But better results are obtained with the technique using an UMZ and direct FM of an LD as the DSB asymmetrical spectrum at UMZ output prevents total cancellation of mixing power. Deeper analysis has shown that the very small fluctuation of mixing power (2.5 dB) can be obtained for an optimum linewidth enhancement factor of 2.7, with a mixing gain still higher than for the MZM or DD-MZM techniques. A good choice of input frequencies depending on the FSR of the UMZ allows high mixing power and good dispersion tolerance. Sensitive degradation occurs when frequencies do not respect this condition any longer.

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LIST OF FIGURES

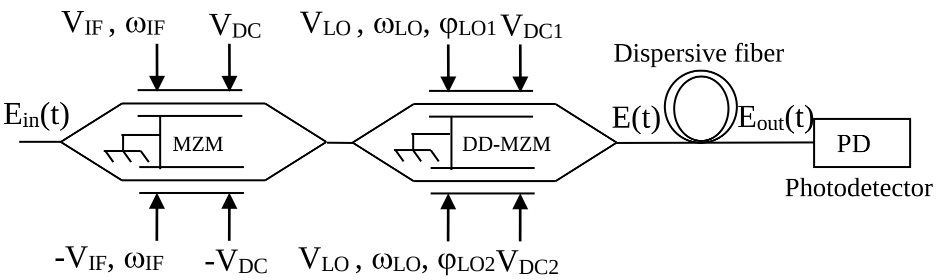


Fig. 1 Scheme of the MZM+DD-MZM upconversion link

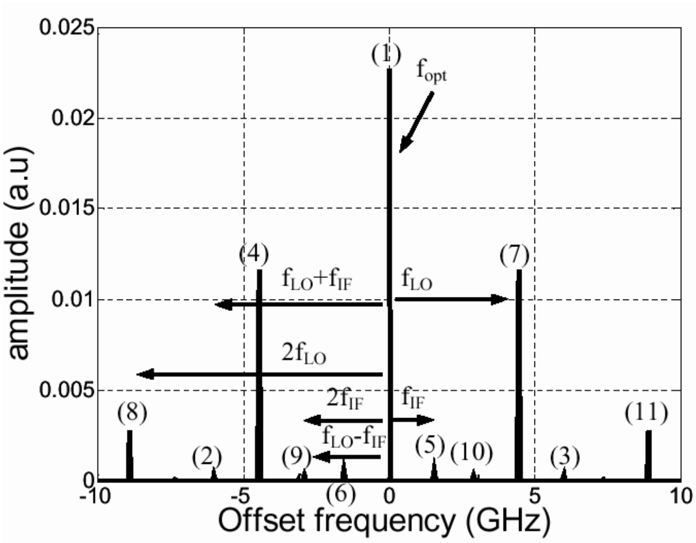


Fig. 2 Optical field (E(t)) spectrum at the output of MZM+MZM

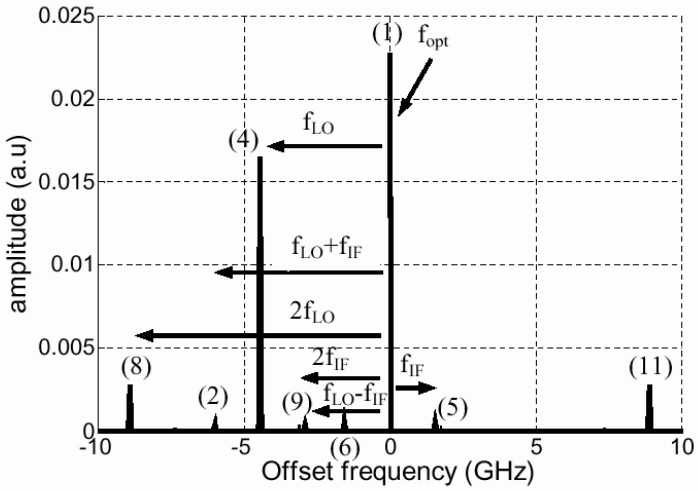


Fig. 3 Optical field (E(t)) spectrum at the output of MZM+DD-MZM

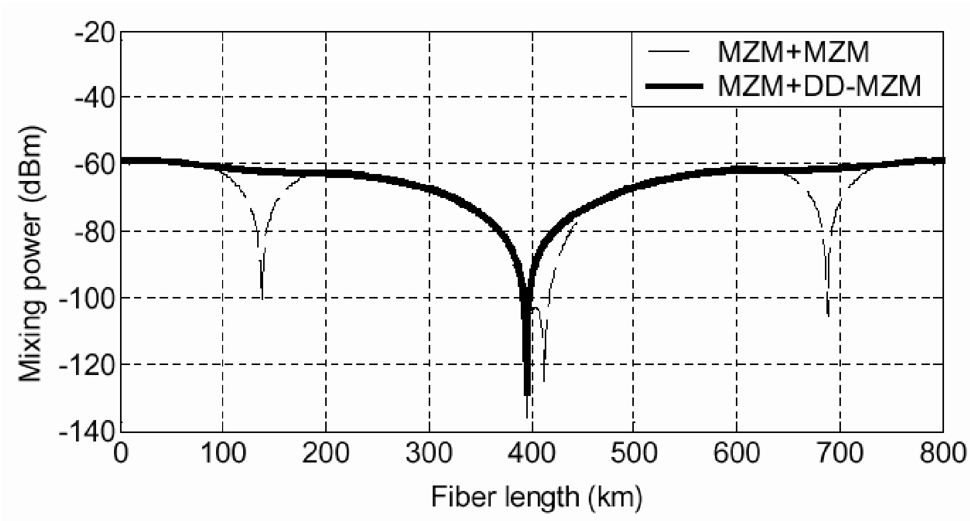


Fig. 4 Simulation of the power of the upconverted signal at 6 GHz as a function of the fiber length for MZM+MZM or MZM+DD-MZM techniques

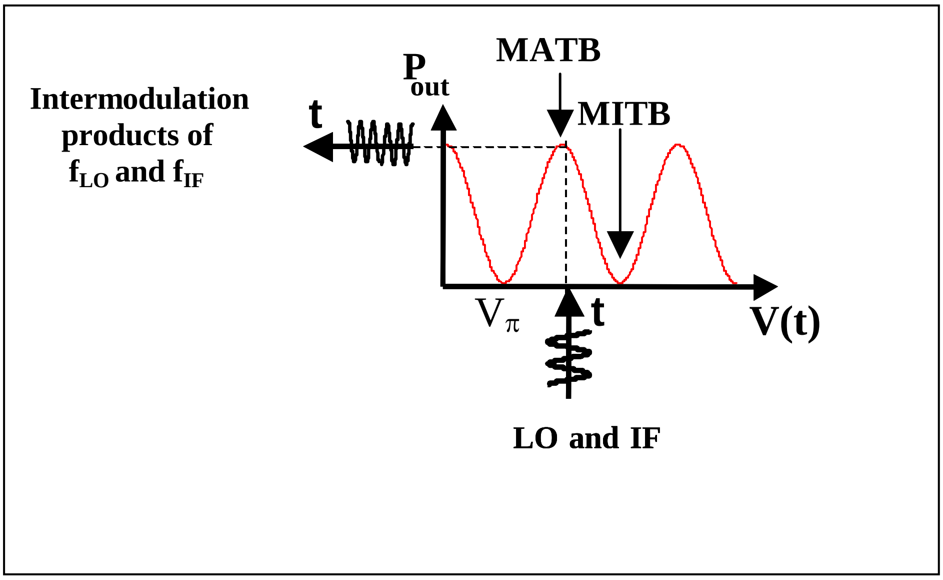


Fig. 5 Definitions of MATB and MITB

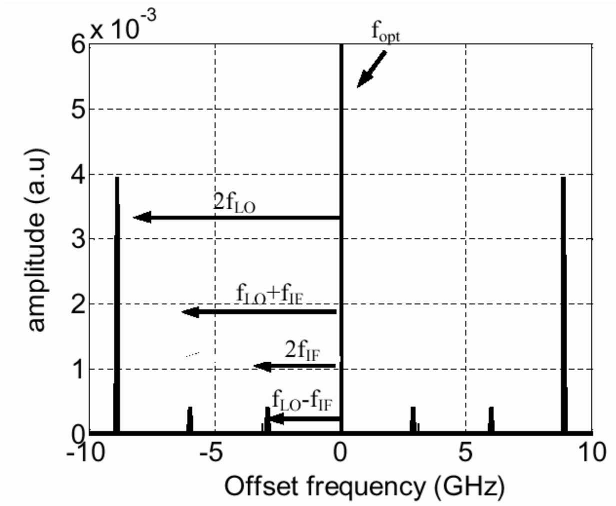


Fig. 6.a Optical field spectrum at the output of MZM at MATB

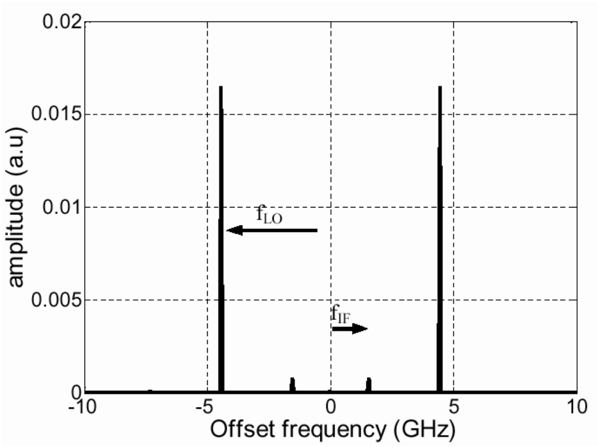


Fig. 6.b Optical field spectrum at the output of MZM at MITB

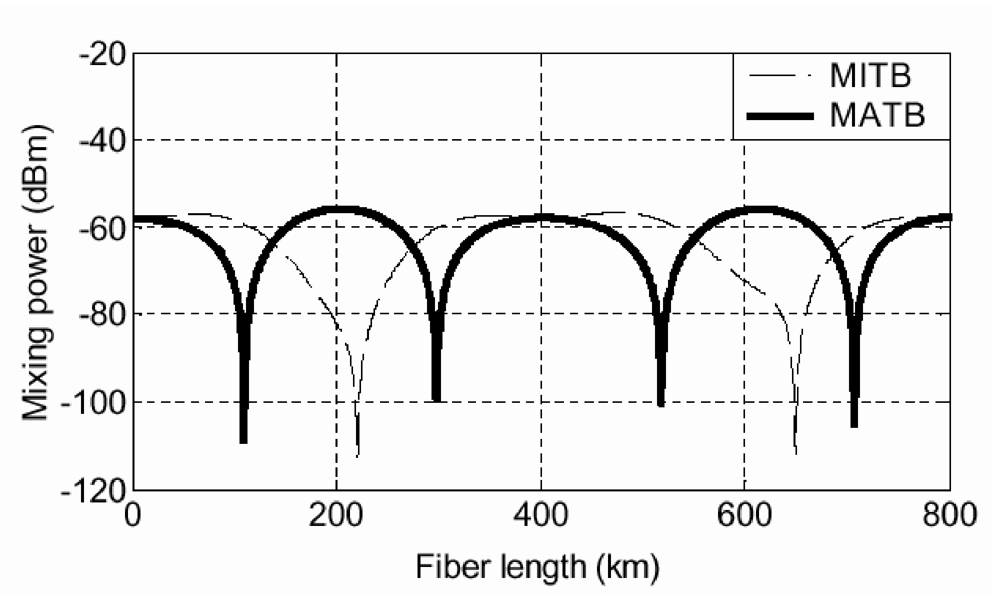


Fig. 7 Simulation of the power of the upconverted signal at 6 GHz as a function of the fiber length for MZM technique

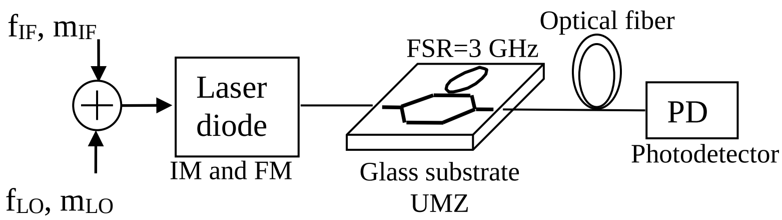


Fig. 8 Scheme of the UMZ upconversion link

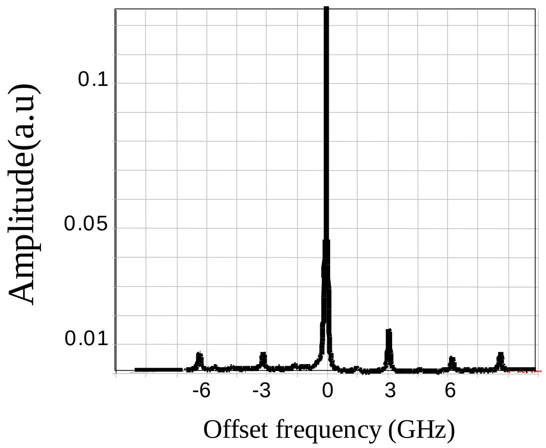


Fig. 9.a Measured optical field spectrum at the output of the UMZ at MATB

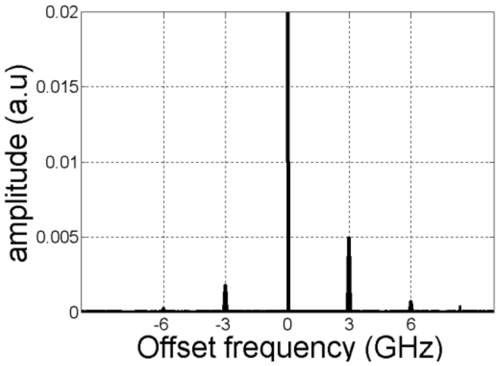


Fig. 9.b Simulated optical field spectrum at the output of the UMZ at MATB

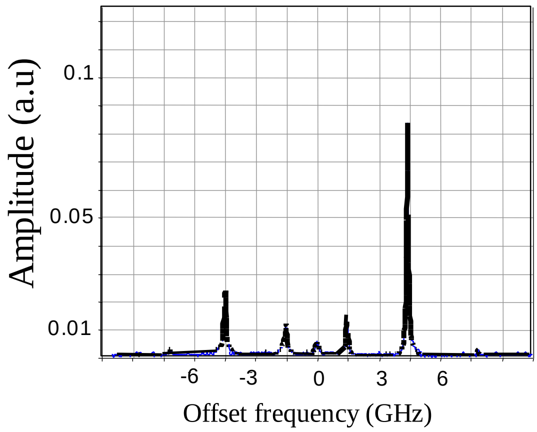


Fig. 10.a Measured optical field spectrum at the output of the UMZ at MITB

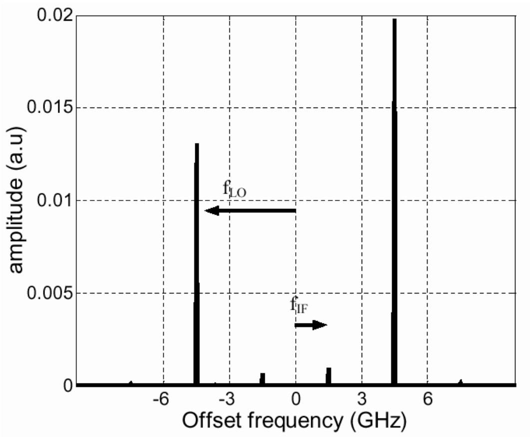
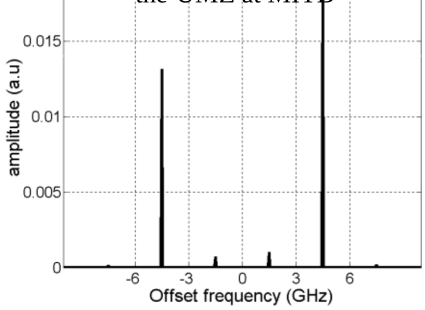


Fig. 10.b Simulated optical field spectrum at the output of the UMZ at MITB



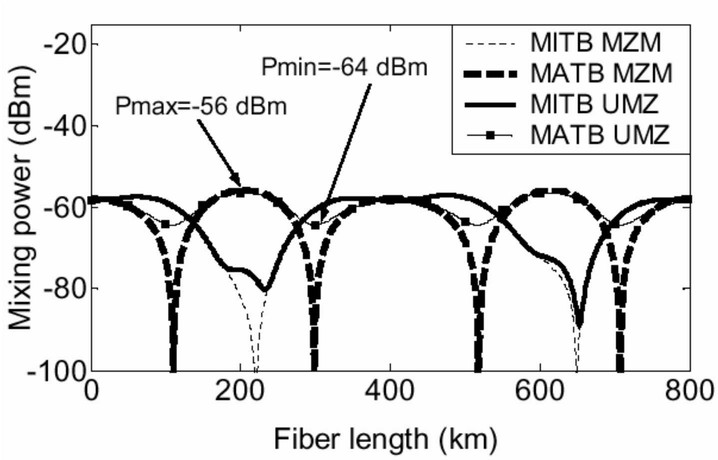


Fig. 11 Simulation of the power of the up-converted signal as a function of fiber length for the UMZ

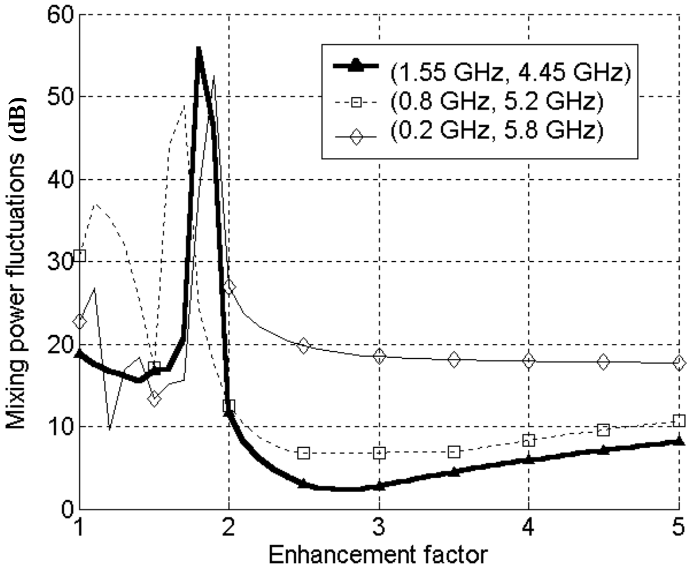


Fig. 12 P_{max}-P_{min} as a function of the linewidth enhancement factor of the laser diode