Experimental demonstration of filtering and multiplexing of microwave signals using a multimode laser diode and chromatic fiber-dispersion parameter

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Abstract. The filtering and multiplexing of microwave signals in the frequency range of 0.01 to 4 GHz is experimentally demonstrated. Filtering is obtained by the spectral characteristics of a 1.5-μm multimode laser diode (MLD) and the chromatic fiber-dispersion parameter. Multiplexing is based on the use of appropriated optical delays generated by the use of a Michelson interferometer that allows a very precise adjustment of the free spectral range (FSR) of the MLD used. Experimental results are validated by means of numerical simulations. To show potential applications in the area of optical communications, a filtered microwave signal is used as a microwave electric-carrier transmitting TV-video signal on a long-distance optical telecommunication system. This is achieved by using an external modulation technique over 28.3 km of a single-mode standard fiber, and using an MLD diode emitting at an optical wavelength around 1.5 μm.
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Subject terms: microwave filters; chromatic fiber dispersion; multimode laser diode; microwave electric carrier; optical fiber telecommunications.

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1 Introduction

Recently, services such as the Internet, broadband access networks, and wireless systems have overcome technical expectations such as data rate, number of channels, and bandwidth. In response, several technological techniques have been investigated to solve these requirements. In this sense and due to the continuous evolution of optoelectronic high-speed devices capable of processing signals at microwave rates and the virtually unlimited bandwidth of optical fibers, optical communication systems are a promising vehicle for achieving these requirements.[1] Because of this, there currently is an increasing interest in the implementation of microwave and millimeter filters capable of carrying tasks equivalent to those of an ordinary microwave filter within radio frequency systems.[2] Although it is well known that fiber chromatic dispersion limits system performance, dispersion effects have been considered in the realization of microwave filters. In this sense, previous works have demonstrated this viability, and they are based mainly on the wavelength tuning of different optical sources combined with optical dispersive elements,[3] multiple fixed wavelength sources combined with tunable dispersive elements,[4] chirped fiber Bragg gratings,[5] and the spectral characteristics of a multimode laser diode and the chromatic fiber-dispersion parameter.[6] This work is based on the results reported in Ref. 6, where the main contribution consists of multiplexing the microwave signals filtered. In summary, we propose and experimentally demonstrate the performance of a novel approach for filtering and multiplexing microwave signals. Filtering is carried out on the spectral characteristics of a multimode laser diode and the chromatic fiber-dispersion parameter, whereas multiplexing is based on the use of appropriate optical delays generated by the use of a Michelson interferometer. Theoretical and experimental results are presented, proving the feasibility of this technique.

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This work has been divided into the following sections. In Sec. 2, the principle of the filtering and multiplexing of microwave signals is presented. Section 3 describes the experimental setup. This section is divided into simulations and experimental results that allow us to validate this technique. To show the potential applications of this type of system in the field of optical telecommunications, this section describes an experimental transmission of video coded on a filtered microwave signal located around 1.0 GHz. For this objective, we use a 28.3-km single-mode standard fiber and a multimode laser diode (MLD) emitting at an optical wavelength of 1550 nm. Finally, conclusions and hints for several possible improvements are given in Sec. 4.

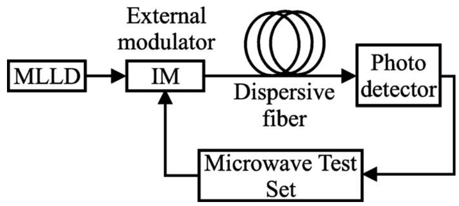

Fig. 1 Scheme used to obtain filtering of microwave signals.[6] MLDD: multi-longitudinal mode laser diode; IM: intensity modulator.

2 Theoretical Basis

As has been previously reported in Ref. 6, the frequency response of the electro-optical system depicted in Fig. 1 is determined by the real part of the Fourier transform of the optical spectrum of the MLD utilized. We refer the reader to this reference for a detailed description of the principle of operation. This frequency response includes a low-pass band centered at zero frequency and is determined as:

$$f_{lp} = \frac{2}{\pi D L \Delta\lambda}, \tag{1}$$

and multiple bandpass windows, centered at the central frequency given by:

$$f_n = \frac{n}{D L \delta\lambda}, \tag{2}$$

where the associated bandwidth of each bandpass window is:

$$\Delta f_{bp} = \frac{4}{\pi D L \Delta\lambda}. \tag{3}$$

In these expressions, D is the chromatic fiber-dispersion parameter in ps/nm-Km, L is the length of the optical fiber in kilometers, $\Delta\lambda$ is the spectral width of the optical source in nanometers, $\delta\lambda$ is the free spectral range (FSR) between two adjacent modes of the MLD in nanometers, and n is an integer $(n=1,2,\ldots)$. As can be seen from Eq. (2), the bandpass windows occur at integer multiples of the central frequency response f_n. Therefore, by knowing the values of D and L, it is possible to adjust the FSR of the MLD for multiplexing the bandpass windows. The most straightforward method to alter the FSR is when the emitted light of the MLD crosses a Michelson interferometer that imprints on the light a static optical delay. Figure 2 illustrates the inclusion of a Michelson interferometer between the MLD and the Mach-Zehnder electro-optic intensity modulator. The optical delay time is given by[7]:

$$\tau = \frac{2(d_2 - d_1)}{c}, \tag{4}$$

where $d=2(d_2-d_1)$ is the difference between the distances traveled by the two waves or the static optical delay, and c is the speed of light on vacuum. Hence, from Eq. (4), and knowing that the periodicity of the spectrum is inversely proportional to the static optical delay, new values of FSR can be computed as:

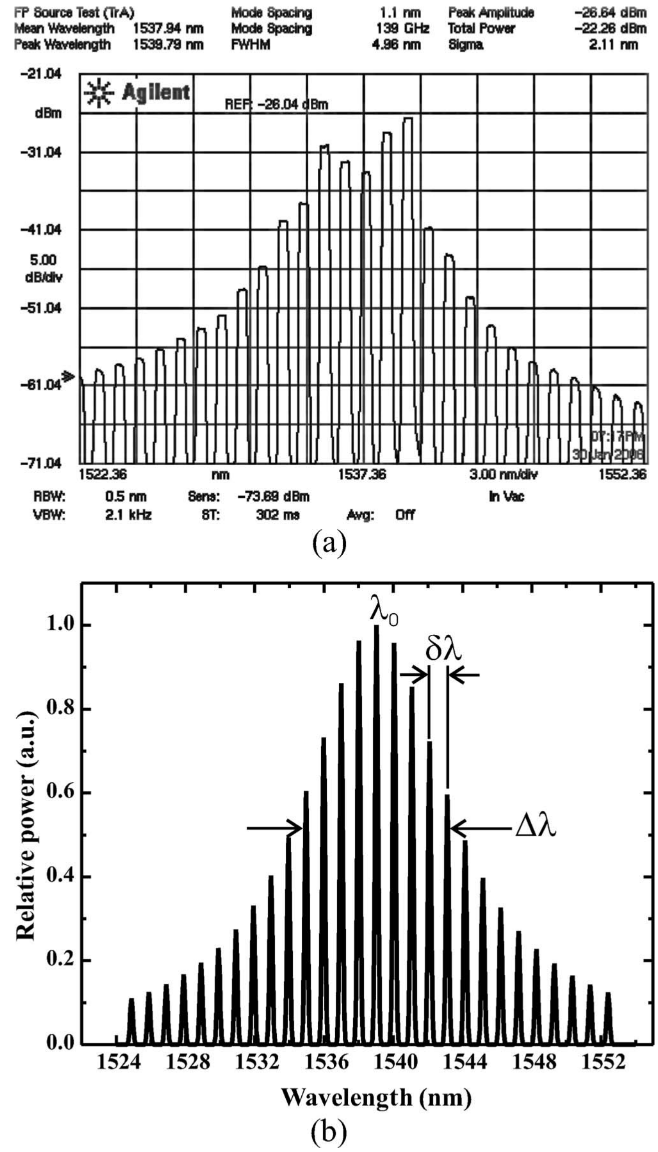

Fig. 3 (a) Power spectrum of the multimode laser diode when operating with an injection current of 25 mA. (b) Power spectrum of the multimode laser diode exhibiting a Lorentzian envelope.

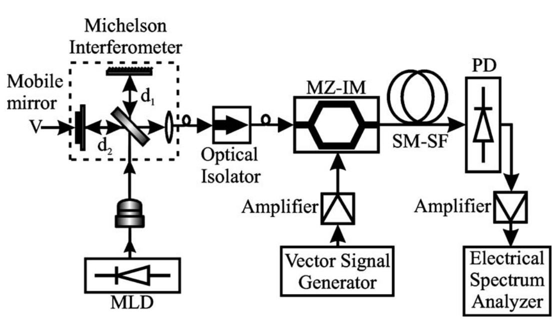

Fig. 2 Experimental setup used for filtering and multiplexing microwave signals.

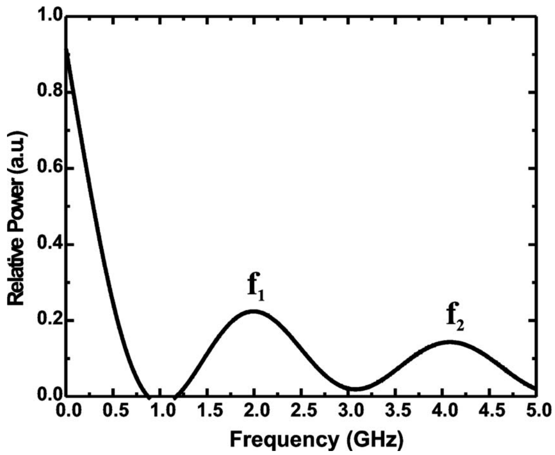

Fig. 4 Simulated frequency response considering the optical spectrum with FSR=1.1 nm (f_1=1.99 and f_2=4.08 GHz).

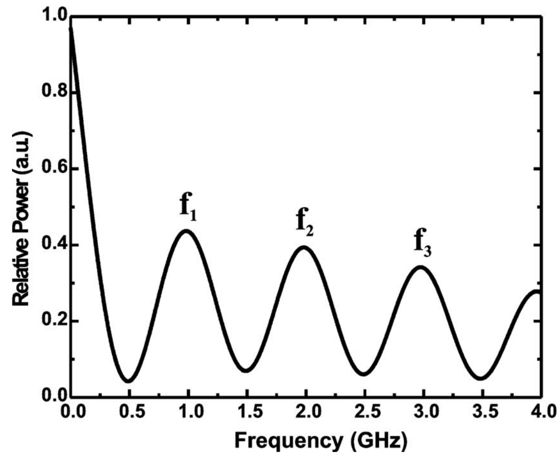

Fig. 5 Simulated frequency response considering the optical spectrum with FSR=2.2 nm (f_1=0.98, f_2=1.98, and f_3=2.97 GHz).

$$\delta\lambda = \frac{\lambda_0^2}{\tau \cdot c} = \frac{\lambda_0^2}{d}, \tag{5}$$

where λ_0 is the central wavelength of the optical source.

3 Experiments

This section is divided into four subsections. In the first subsection, we present the optical characterization of the MLD used in this experiment. The optical information obtained is used in the second subsection, where the system's frequency response is evaluated by means of numerical simulations. Next, in the third subsection, we present the experimental results corresponding to the filtering and multiplexing of microwave signals. Finally, in the fourth subsection, we describe the experimental transmission of a video signal using a filtered microwave signal as an electric carrier.

3.1 *Optical Characterization of the Multimode Laser Diode*

The MLD used in this experiment (Mitsubishi ML976H6F) was characterized by means of an optical spectrum analyzer (Agilent, model 86143B) to determine its optical characteristics. Figure 3(a) corresponds to the emission spectrum of the MLD operating at a drive current of 25 mA, where λ_0 =1539.79 nm, FSR=1.1 nm, and $\Delta\lambda$=4.96 nm.

3.2 *Numerical Simulations*

The emission spectrum corresponding to Fig. 3(a) can be modeled by an MLD that exhibits a Lorentzian envelope and that can be expressed in terms of optical power spectrum $P(\sigma)$, where σ is the wave number ($\sigma=1/\lambda$) as[8]

$$P(\sigma) = \frac{2\Delta\sigma P_0}{\pi\Delta\sigma^2 + 4\pi(\sigma-\sigma_0)^2} \cdot \left[\frac{2P_0}{\delta\sigma\sqrt{\pi}} \exp\left(-\frac{4\sigma^2}{\delta\sigma\sqrt{\pi}}\right) \otimes \sum_{-\infty}^{\infty} \delta(\sigma - n\partial_0) \right], \tag{6}$$

where P_0 is the maximum power, $\sigma_0=1/\lambda_0$ is the center wave number, $\Delta\sigma=\Delta\lambda/\lambda_0^2$ is the spectral width at half maximum, $\delta\sigma$ is the spectral width of each mode, ∂_0 is the FSR, and $\otimes$ stands for the convolution product. The first term corresponds to the envelope, whereas the term between brackets corresponds to the impulse train of modes. The use of Eq. (6) allows the modeling of the optical spectrum illustrated in Fig. 3(b), where λ_0=1539 nm and $\delta\lambda$ =1.1 nm. If the real part of the Fourier transform of Eq. (6) is obtained, and considering 28.3 km of single-mode standard optical fiber (SM-SF) with chromatic fiber-dispersion parameter D=17 ps/nm-km at 1550 nm, we obtain the trace of Fig. 4 that corresponds to the frequency response of the system. In this figure, we can clearly appreciate the presence of a low-pass band centered at zero frequency and

Table 1 Location of the bandpass windows in function of the FSR used.

Frequency (GHz)	Theoretical $f_n=n/DL\delta\lambda$		Simulation		Experimental	
	$\delta\lambda$=1.1 nm	$\delta\lambda$=2.2 nm	$\delta\lambda$=1.1 nm	$\delta\lambda$=2.2 nm	$\delta\lambda$=1.1 nm	$\delta\lambda$=2.2 nm
f_1	1.88	0.94	1.99	0.98	2.01	0.95
f_2	3.77	1.88	4.08	1.98	-	1.92
f_3	5.66	2.83	-	2.97	-	2.92

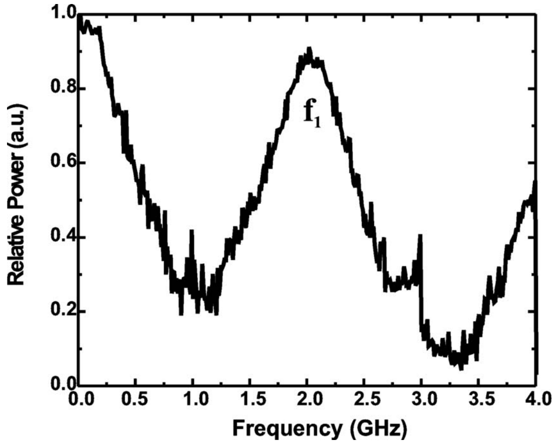

Fig. 6 Experimental frequency response considering the optical spectrum with FSR=1.1 nm (f_1=2.01 GHz).

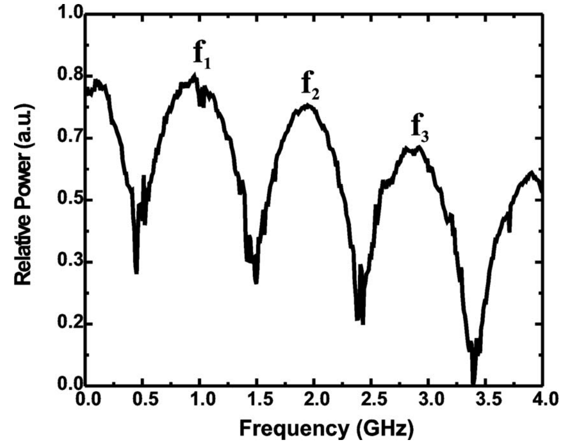

Fig. 8 Experimental frequency response considering the optical spectrum with FSR=2.2 nm (f_1=0.95, f_2=1.92, and f_3=2.92 GHz).

two bandpass windows centered at f_1=1.99 GHz and f_2 =4.08 GHz. Next, if the FSR is selected to $\delta\lambda$=2.2 nm, the result of the numerical simulation shows the presence of three bandpass windows on the same frequency range (0 to 4 GHz), as illustrated in Fig. 5. In this last case, the bandpass windows are centered at f_1=0.98 GHz, f_2=1.98 GHz, and f_3=2.97 GHz. In both simulations, the associated bandwidth for these bandpass windows is around 500 MHz. These results are in good agreement with the analytical values given by the use of Eqs. (1)–(3), permitting the validation of the effect of multiplexing for the filtered microwave signals.

3.3 *Filtering and Multiplexing of the Microwave Signals*

To test the validity of this technique, in a first step, we have measured the frequency response of the experimental system depicted in Fig. 1. We have used 28.3 km of SM-SF exhibiting a chromatic fiber-dispersion parameter D =17 ps/nm-km at 1550 nm. In this case, we have used the

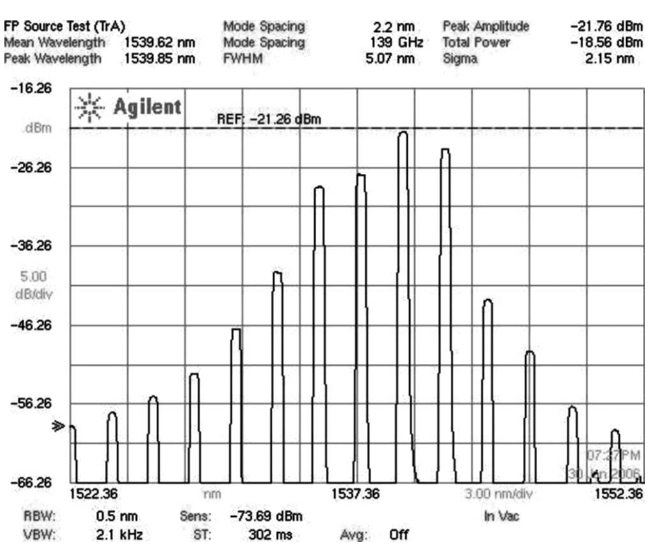

Fig. 7 Channeled power spectrum corresponding to a static optical delay of d=0.55 mm.

MLD previously characterized in Sec. 3.1 that exhibits $\delta\lambda$=1.1 nm. Figure 6 corresponds to the frequency response measured where the presence of a bandpass window centered to 2.01 GHz is near to the value obtained by the use of Eq. (2) and with the simulation result. In a second step, we have used the experimental setup shown in Fig. 2, where a Michelson interferometer is included. In this case, when the light passes through the interferometer, a static optical delay (d) is imprinted on the light. In agreement with Eq. (5), the optical delay is determined by the difference between the distances traveled by the two waves. As we have previously indicated, an appropriate static optical delay permits us to obtain a new value of FSR. In this case, we have displaced the mobile mirror to obtain d =1.07 mm approximately, and by the use of Eq. (5), $\delta\lambda$ =2.2 nm is obtained. Figure 7 corresponds to the filtered emission spectrum obtained in this last case. The light issued from the Michelson interferometer is modulated by a 10-GHz bandwidth Mach-Zhender intensity modulator (MZ-IM). An rf signal sweep between 0.01 to 4 GHz at 0 dBm issued from a vector signal generator (Agilent model E4438C) is applied to the modulator. The rf modulated light passes through a single-mode standard optical fiber and is detected at the end by a fast photodetector (New Focus, model 1414). After electrical amplification,

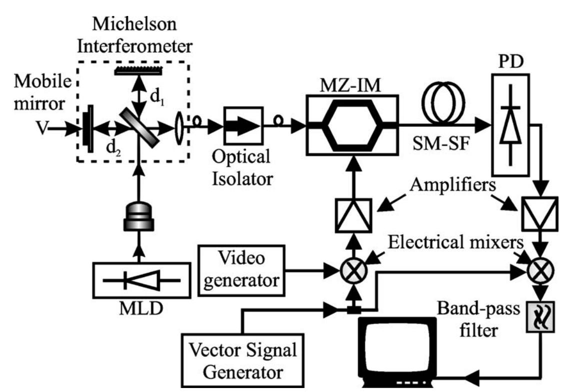

Fig. 9 Experimental setup employed for TV-video signal transmission.

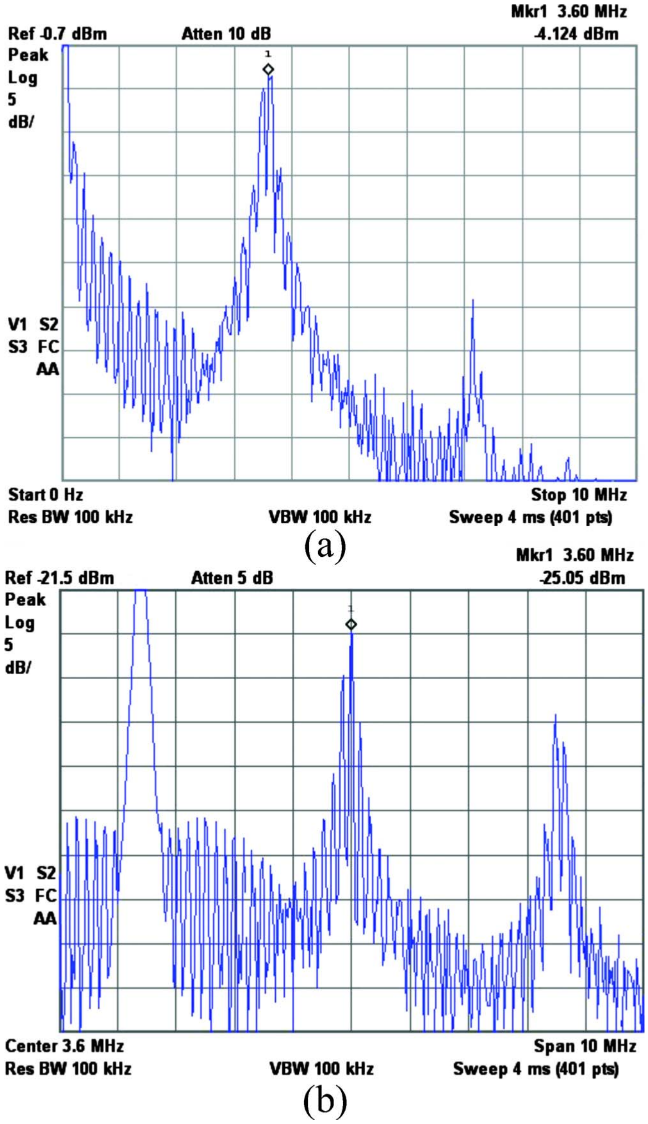

Fig. 10 Electrical spectrum of the TV signal: (a) transmitted, $p=-4.124$ dBm and (b) recovered, $p=-25.05$ dBm.

the signal is launched to an electrical spectrum analyzer, where the frequency response is measured. Figure 8 illustrates the experimental frequency response where a low-pass band and three bandpass windows can be observed. The presence of the first lobe centered to $f_1=0.95$ GHz is due to the optical delay introduced on the emission spectrum of the MLD. Due to the periodicity of the optical spectrum, lobes (bandpass windows) centered at $f_2=1.92$ and $f_3=2.92$ GHz are clearly seen. These experimental results are again in good agreement with the numerical simulation showed previously in Sec. 3.2 as well as with the analytical values given by Eqs. (1)–(3). Finally, Table 1 summarizes the theoretical, simulation, and experimental results corresponding to the location of the bandpass windows. The difference observed between these values is justified by the uncertainty of the real value of the length of the optical fiber used.

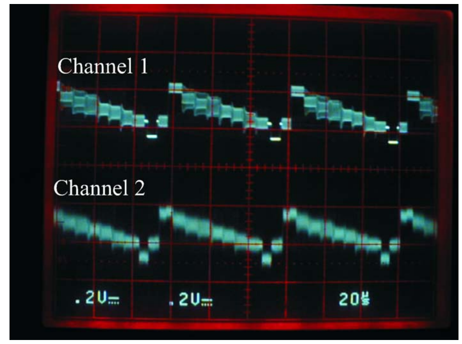

Fig. 11 Experimental results of the TV-video signal transmission. Channel 1: transmitted signal; channel 2: recovered signal.

3.4 *Experimental Transmission of Video*

To show potential applications in the field of optical telecommunications, the system was tested by transmitting a TV-video signal of a frequency of 3.60 MHz using the first bandpass window centered around 1.0 GHz. The scheme used for this goal is depicted in Fig. 9. The TV-video signal is passed onto an electrical mixer to add a carrier frequency of 1.0 GHz, amplified and applied to the Mach-Zehnder intensity modulator. The modulated optical signal is transmitted across the 28.3 km of dispersive optical fiber. At the receiver, the modulated light is photodetected, amplified, and mixed to remove the carrying signal of 1 GHz, and finally launched to the electrical spectrum analyzer where it is analyzed to measure the power level. Figure 10 shows the spectrums of the TV-signal transmitted (−4.124 dBm), mixed with the signal of 1 GHz, and recovered (−25.025 dBm). It is evident that the figure of merit or signal-to-noise ratio (SNR) can be improved substantially with the addition of another stage of electrical amplification at the end of the link. This added stage will allow a precise quantification for the SNR parameter. The use of the electrical bandpass filter permits the recovered video signal to be displayed directly on an oscilloscope or on a standard TV monitor. Figure 11 corresponds to the screen of the oscilloscope showing the TV signal transmitted and recovered. The TV signal was recovered on a standard TV monitor without noticeable degradation compared to direct injection. Finally, under a similar principle, the other bandpass windows can be used as electrical carriers.

4 Conclusions

In this work, we report an experimental electro-optical setup that permits the filtering of microwave signals supported by the use of a chromatic fiber-dispersion parameter, the length of the optical link, and the free spectral range of the multimode laser diode used. Multiplexing is achieved by introducing an optical delay on the optical spectrum by use of a Michelson interferometer. The periodicity of the optical spectrum confirms that the frequency response exhibits bandpass windows that can be extended beyond 4 GHz (in this work, the frequency range was limited by the bandwidth of the electrical amplifiers used). The electro-optical response of the system was measured and compared to the one obtained by simulation. The comparisons show good agreement with the analytical prediction given by Eq. (2). To show a potential application, a TV-video signal is successfully transmitted on the microwave signal filtered near 1 GHz. In this case, the microwave signal acts as an electric carrier. The transmission is tested and the TV-video signal is recovered without noticeable quality degradation. It is also concluded that the main limitations in the system reported here come from the requirement of a precise displacement of the Michelson interferometer. As future work, it will be necessary to replace the Michelson interferometer by a segment of birefringent optical fiber to obtain an all-fiber system. This will allow a substantial improvement of optical levels to guarantee a good optical transmission, and by consequence to improve the signal-to-noise ratio (SNR) of the system. Under a similar principle, this technique can be easily extended to the use of an MLD emitting at 1300 nm and single-mode dispersion-shifted fiber. As a result, this kind of system could operate in the second and third optical window communication settings.

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