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Transmission system for distribution of video over long-haul optical point-to-point links using a microwave photonic filter in the frequency range of 0.01–10 GHz

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ABSTRACT

We experimentally demonstrate the use of an electro-optical transmission system for distribution of video over long-haul optical point-to-point links using a microwave photonic filter in the frequency range of 0.01–10 GHz. The frequency response of the microwave photonic filter consists of four band-pass windows centered at frequencies that can be tailored to the function of the spectral free range of the optical source, the chromatic dispersion parameter of the optical fiber used, as well as the length of the optical link. In particular, filtering effect is obtained by the interaction of an externally modulated multimode laser diode emitting at 1.5 μm associated to the length of a dispersive optical fiber. Filtered microwave signals are used as electrical carriers to transmit TV-signal over long-haul optical links point-to-point. Transmission of TV-signal coded on the microwave band-pass windows located at 4.62, 6.86, 4.0 and 6.0 GHz are achieved over optical links of 25.25 km and 28.25 km, respectively. Practical applications for this approach lie in the field of the FTTH access network for distribution of services as video, voice, and data.

1. Introduction

Currently, faced with the high demand for telecommunications services with high data transfer rates and immediate access, photonics telecommunication systems arise as a competitive alternative for the processing, transmission and distribution of an enormous amount of information [1]. Inherent features of these kinds of systems, such as lower losses, broader bandwidth and immunity to electromagnetic interference, make them a very interesting choice compared to electrical conventional systems [2]. In addition, another application that attracts interest in research and, which complements the photonic telecommunication systems is the so called FTTH (Fiber-To-The-Home) access network [3,4]. FTTH has been envisioned for delivering broadband services delivering the communications signal over optical fiber from the operator's switching equipment directly to a home or business building. By the end of 2007, there were 29 million subscribers to services supplied by FTTx networks, and by 2013, the number is expected to grow to over 100 million subscribers, hence the importance of this network. The factors previously described, together with the increasing demand for multiple communications applications with a great amount of information associated, as well as the high bit rates, justify the introduction of microwave photonic filters into the access networks [5–8]. In this sense, we focus our attention on the results recently reported in [9], where the authors have successfully demonstrated that the use of a multimode laser diode associated to the chromatic fiber dispersion parameter and the length of the optical link allows the filtering of microwave signals in the frequency range of 0.01–4.0 GHz. Now, in this paper, we report the use of this microwave photonic filter for distribution of video over long-haul optical point-to-point links in the frequency range of 0.01–10 GHz. It is very important to remark that the work referenced in [9] describes a fiber-radio system operating at 2.8 GHz based in the same microwave photonic filter (MPF) used in this work. However, the main difference of this paper with regard to [9] resides in the fact that now we are describing a long-haul optical point-to-point link composed by two branches, allowing in this way a simultaneously transmission of TV-signal. Inclusively, now we are overcoming a technical limitation that was imposed by the frequency range provided by the microwave generator in [9], where the frequency range was limited at 4 GHz. To show a potential application of this approach in the field

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of photonics telecommunications, filtered microwave signals are used as electrical carriers to transmit TV-signal over long-haul optical point-to-point links. For that purpose, transmission of TV-signal coded on the microwave band-pass windows located at 4.62 and 6.86 GHz, as well as at 4.0 and 6.0 GHz are achieved over long-haul optical links of 25.25 km and 28.25 km, respectively. After a brief refreshment of the basic operation of the MPF carried in Section 2, we devote Section 3 to describing a series of experiments that corroborates the approach here proposed. Finally some conclusions are derived in Section 4.

2. Principle

The basic scheme of the microwave photonic filter (MPF) used in this work is shown in Fig. 1. The reader can find a very detailed description of the principle of operation of this MPF in reference [9], and so here, we indicate only a comprehensive analysis of the influence of an optical source of multimode spectrum over the frequency response of the MPF. The light emitted by the optical source is modulated by a Mach–Zehnder Intensity Modulator (MZ-IM) operated on the linear region with an electric signal $V_m = 1 + 2m\cos(\omega_m t)$ of electrical frequency ω_m, where m is the modulation index related to the electrical input signal by $m = \pi(v(t)/V_\pi)$, with V_π the half-wave voltage of the MZ-IM. Assuming the optical fiber as a linear time invariant system characterized by its propagation constant (β) and its length (L), then the total average intensity at the end of the optical fiber is determined as [9]

$$I_L = I_0 + m\cos\left(\frac{1}{2}\omega_m^2\beta_2 L\right)\cdot 2\int_0^\infty S(W)\cos(WZ)\,dW \tag{1}$$

where I_0 is the average intensity of the optical source, $W = \omega - \omega_0$ with $dW = d\omega$, and $Z = \omega_m\beta_2 L$, with $\beta_2 = -D(\lambda^2/2\pi c)$, where λ is the wavelength, D is the chromatic dispersion parameter of the optical fiber, and c is the speed of light in a medium of refractive index n given as $c = c_0/n$, where c_0 is the speed of light in free space. Therefore, Eq. (1) can be written as

$$I_L = I_0 + m\cos\left(\frac{1}{4\pi c}\omega_m^2\lambda^2 DL\right)F.T.\{S(W)\} \tag{2}$$

Thus, the frequency response of the MPF is determined by the second term of Eq. (2), which is proportional to the Fourier transform of the spectrum of the optical source. In particular, a multimode laser diode (MLD) exhibiting a Gaussian envelope and modes centered at an angular frequency ω_0 can be modeled as [10]

$$S(W) = \frac{2S_0}{\Delta_\omega\sqrt{\pi}}\exp\left(-\frac{4(\omega-\omega_0)^2}{\Delta_\omega^2}\right)\cdot\left[\frac{2}{\sigma_\omega\sqrt{\pi}}\exp\left(-\frac{4(\omega-\omega_0)^2}{\sigma_\omega^2}\right) * \sum_{n=-\infty}^{\infty}\delta(\omega - n\delta_\omega)\right] \tag{3}$$

where S_0 is the maximum power emission, Δ_ω is the full width at half maximum (FWHM) of the spectrum, σ_ω is the FWHM of each mode, δ_ω is the free spectral range (FSR) between the modes and $*$ denotes the convolution operation. The term between square parentheses corresponds to a train of impulses indicating a periodic pattern. By using variables Z and W, as defined previously, the Fourier transform of Eq. (3) is

$$F.T.\{S(W)\} = \exp\left(-\left(\frac{\Delta_\omega Z}{4}\right)^2\right) * \left[\exp\left(-\left(\frac{\sigma_\omega Z}{4}\right)^2\right)\cdot\left(\frac{1}{\delta_\omega}\sum_{n=-\infty}^{\infty}\delta\left(Z - n\frac{2\pi}{\delta_\omega}\right)\right)\right] \tag{4}$$

The location of each impulse determines the central frequency of the nth band-pass filtered in the frequency response of the MPF. If these values are denoted as f_n they can be determined by equating $Z = n(2\pi/\delta_\omega)$. In this way, we obtain

$$f_n = n\left(\frac{1}{DL\delta_\lambda}\right) \tag{5}$$

where n is a positive integer ($n = 1,2,\ldots$), and δ_λ is the FSR of the spectrum given in nm.In addition, the first term of Eq. (3), allows us to determine the low-pass band of the MPF, and so, the Fourier transform corresponding to this term is

$$F.T.\{S(W)\} = \exp\left[-\left(\frac{\Delta_\omega\omega_m\beta_2 L}{4}\right)^2\right] \tag{6}$$

This is also a Gaussian function. Equating (6) with $S(\omega) = \ln 2$

$$-\left(\frac{\Delta_\omega\omega_m\beta_2 L}{4}\right)^2 = \ln 2 \tag{7}$$

For finding the value of the frequency f_m that yields that condition, it is necessary to express $\omega_m = 2\pi f_m$. However, this in turn, yields an expression that can be reduced by expressing Δ_ω in terms of $\Delta\lambda$ and β_2 in terms of chromatic dispersion parameter D. For Δ_ω this is done as follows: given $d\omega/d\lambda = -(2\pi c/\lambda^2)$, it is possible to establish the following correspondence

$$d\omega = -\frac{2\pi c}{\lambda^2}d\lambda \Longleftrightarrow \Delta_\omega = -\frac{2\pi c}{\lambda^2}\Delta\lambda \tag{8}$$

Now, for β_2, given that the group velocity, $v_g = L/\tau_g$ where τ_g is the group delay related to $\beta(\omega_m)$ as $\tau_g/L = d\beta(\omega_m)/d\omega$, and its derivative is $(d\tau_g/d\omega)/L = d^2\beta(\omega_m)/d\omega^2 = \beta_2$, then $(1/L)(d\tau_g) = d\omega\beta_2$. Thus, the derivative of this expression by $d\lambda$ is $(1/L)(d\tau_g/d\lambda) = (d\omega/d\lambda)\beta_2$. Furthermore, the chromatic dispersion parameter as a function of the wavelength is defined as $D = (1/L)(d\tau_g/d\lambda)$. This means that $\beta_2 = -D(\lambda^2/2\pi c)$. Then, by substituting $\omega_m = 2\pi f_m$, Δ_ω, as defined in Eq. (8), and the expression for $\beta_2$in Eq. (7), the frequency f_m, corresponds to the low-pass frequency response of the MPF f_{lp} is found as

$$f_{lp} = -\frac{2\sqrt{\ln 2}}{\pi DL\Delta\lambda} \tag{9}$$

Thus, the bandwidth of each band-pass window will double that of Eq. (9); that is, the corresponding bandwidth at -3 dB of the nth band-pass window is

$$\Delta f_{bp} = -\frac{4\sqrt{\ln 2}}{\pi DL\Delta\lambda} \tag{10}$$

In summary, the results obtained above indicate that the transfer function MPF is composed of a low-pass band centered at zero frequency and multiple band-pass windows that depend on the spectral profile of the optical source, on the chromatic dispersion

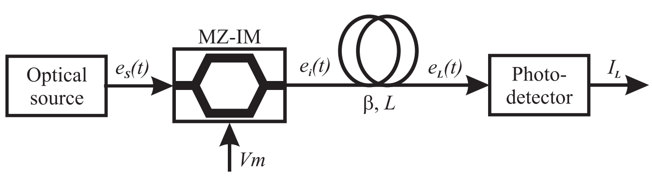

Fig. 1. Basic topology of the microwave photonic filter [9].

value of the optical fiber, and on its length. At this point, it is very important to remark on the usefulness of the chromatic dispersion parameter of the optical fiber.

3. Experiment result

This section is divided into two subsections. First, we present the optical characterization of the MLD used in this experiment, as well as the experimental evaluation of the frequency response of the MPF in the frequency range of 0.01–10 GHz. Next, we describe the experimental transmission of a TV-signal at 4.62, 6.86, 4.0 and 6.0 GHz using filtered microwave signals as an electric carrier.

3.1. Experimental evaluation of the frequency response of the MPF

Fig. 2 corresponds to the optical spectrum of the MLD used in this experiment (Thorlabs, model S1FC1550) registered by using an Optical Spectrum Analyzer (Anritsu, model MS9740A). The main values at an optical power of 1.5 mW are: $\lambda = 1.533$ nm, FWHM = 4.10 nm, and $\delta_\lambda = 1.1$ nm. The use of a laser diode temperature-controller (Thorlabs, model LTC100-C) allows us to guarantee the stability of the optical parameters to thermal fluctuations. To demonstrate the effect of filtering, and considering lengths of L = 25.24-km and L = 28.25-km of single-mode-standard-fiber (SM-SF) exhibiting a chromatic fiber-dispersion parameter of D = 15.81 ps/nm-km, the use of Eq. (5) allows us to determine the value corresponding to the central frequency of the first band-pass for each optical fiber.

$$f_1 = \frac{1}{DL\delta_\lambda} = \frac{1}{(15.81 \times 10^{-12}\ \text{seg/nm km}) \cdot (25.24\ \text{km}) \cdot (1.1\ \text{nm})} = 2.27\ \text{GHz}$$

$$f_1 = \frac{1}{DL\delta_\lambda} = \frac{1}{(15.81 \times 10^{-12}\ \text{seg/nm km}) \cdot (28.25\ \text{km}) \cdot (1.1\ \text{nm})} = 2.03\ \text{GHz}$$

According to Eq. (5) the n-th band pass windows are: $f_n = n(2.27)$ GHz, and $f_n = n(2.03)$ Ghz with $n = 1, 2, \ldots$ the frequency response of the MPF must contain four well-defined bands in the frequency range of 0.01–10 GHz, for both cases. On the other hand, Eq. (9) allows us to determine the value corresponding to the low-pass band for each optical fiber as

$$f_{lp} = \frac{2\sqrt{ln2}}{\pi DL\Delta\lambda} = \frac{2\sqrt{ln2}}{(\pi)(15.81 \times 10^{-12}\ \text{seg/nm km}) \cdot (25.24\ \text{km}) \cdot (4.10\ \text{nm})} = 323.95\ \text{MHz}$$

$$f_{lp} = \frac{2\sqrt{ln2}}{\pi DL\Delta\lambda} = \frac{2\sqrt{ln2}}{(\pi)(15.81 \times 10^{-12}\ \text{seg/nm km}) \cdot (28.25\ \text{km}) \cdot (4.10\ \text{nm})} = 289.43\ \text{MHz}$$

Finally, and according to Eq. (10), the corresponding bandwidth of each band-pass window are: Δf_{by} = 647.90 MHz, and Δf_{by} = 578.87 MHz.

In order to evaluate experimentally the frequency response of the MPF, the set-up illustrated in Fig. 3 is assembled. The output from the MLD is injected into the optical isolator (OI) in order to avoid reflections to the source. Since the MZ-IM (PHOTLINE, model MXAN-LN-20) is polarization-sensitive, a polarization controller (PC) is used to maximize the modulator output power. The optical signal is injected into the MZ-IM. The microwave electrical signal for modulating the optical intensity is supplied by a Microwave Signal Generator (Anritsu, model MG3692C) in the frequency range of 0.01–10 GHz at 10 dBm. The intensity-modulated optical signal is divided by using an optical coupler 50:50 allowing in this way light to be injected into two bobbins (SM-SF1 and SM-SF2) of different length. In our experiment, Branch 1 is composed of a SM-SF of length L = 25.24-km, whereas that Branch 2 is composed of a SM-SF of length L = 28.25-km. At the end of each link, the optical signal is applied to a fast photo-detector (Miteq, model DR13) and its output connected to an electrical amplifier (Minicircuits, ZVA-183+), and finally launched to the electrical spectrum analyzer (Anritsu, model MS2830A) in order to measure the frequency response of the MPF. Fig. 4 illustrates the measured frequency response corresponding to the different lengths of optical fiber used where the presence of four well-formed band-pass bands is clearly appreciable, for each case. Due to the periodicity of the optical spectrum, for L = 25.24-km, band-pass windows centered at f_1 = 2.31 GHz, f_2 = 4.62 GHz, f_3 = 6.86 GHz, and f_4 = 9.14 GHz are clearly seen. Whereas that for L = 28.25-km, band-pass windows centered at f_1 = 2.01 GHz, f_2 = 4.01 GHz, f_3 = 6.03 GHz, and f_4 = 8.05 GHz are clearly distinguished. These results are in good agreement with the analytical values given by the use of Eq. (5). The decrease in power level corresponding to the optical link of 28.25 km (Branch 2) with regard to the optical link of 25.24 km (Branch 1) is justified precisely by the difference in length. In order to compensate the difference between these curves we could increment the number of amplifiers used at the end of the link for the case of the optical link of 28.25 km. In other words; we could adjust the levels of detected power using an appropriate numbers of amplifiers.

In summary, our experimental results agree well with the calculated results based on theory. The average bandwidth of 613.38 MHz associated to the band-pass windows allows us to guarantee enough bandwidth in case of fluctuations (in the order of nanometers) between mode-spacing. This consideration permits us to guarantee good stability for the MPF. Finally, Table 1 summarizes the theoretical and experimental results corresponding to the

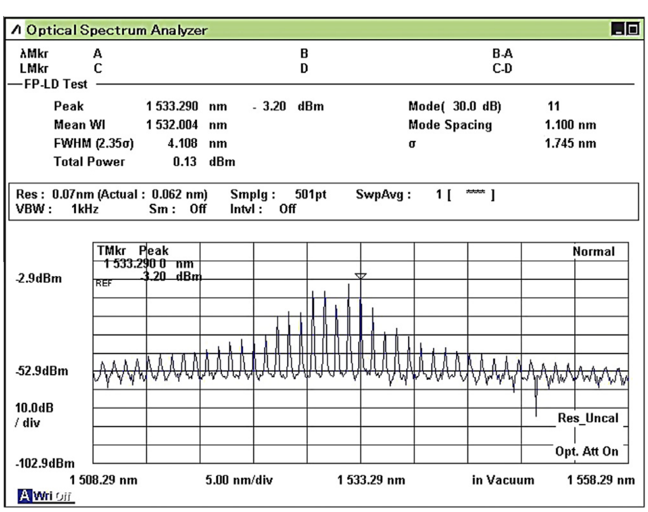

Fig. 2. Measured optical spectrum.

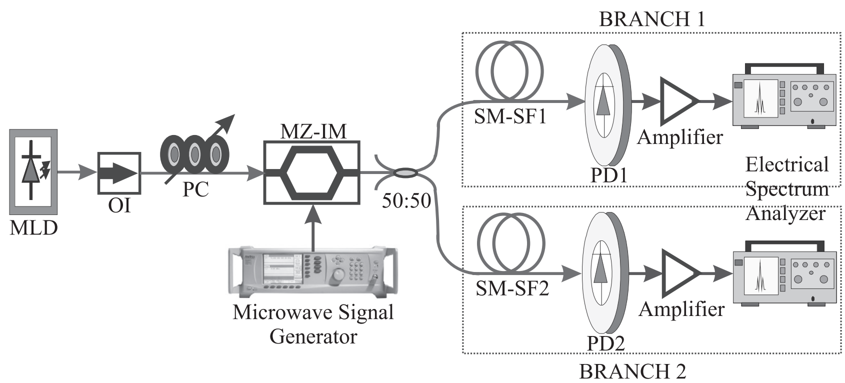

Fig. 3. Proposed experimental setup composed of two branches for filtering microwave signals.

location of each band pass window as well as the corresponding error rate.

By analyzing these data, the small deviation between the theoretical and experimental values is justified by the uncertainty of the real value of the length of the optical fibers used. The difference between the theoretical and experimental value of f_n was determined by means of the relationship

$$\%\text{error}, \quad f_n = \frac{|f_{n,\text{theoretical}} - f_{n,\text{experimental}}|}{f_{n,\text{theoretical}}} \times 100\%$$

3.2. Experimental transmission of TV-signal over a long-haul optical link

This subsection is also sub-divided. First, we describe the experiment corresponding to the TV-signal transmission using the band-pass windows located at 4.62 and 6.86 GHz by Branch 1. Next, we explain the same transmission but using the band-pass windows located at 4.0 and 6.0 GHz corresponding to Branch 2.

3.2.1. Experimental transmission of TV-signal using Branch 1

Following the scheme of Fig. 3, the block scheme of the TV-signal transmission is shown in Fig. 5. The use of each branch is selected by means of the switch, i.e. in this case the switch is placed in position 1.

The microwave signal generator provides a signal of 4.62 GHz at an electrical power of 15 dBm that is used as the electrical carrier and demodulated signal. This electrical signal is separated by using a power divider. Part of this electrical signal is transmitted via cable in order to act as a demodulated signal, and the rest is mixed (mixer 1) with an analog NTSC (National Television System Committee) TV-signal of 67.25 MHz (Channel 4). The resulting mixed electrical signal is then applied to the electrodes of the MZ-IM for modulating the light emitted by the MLD. The modulated light is coupled into the 25.24-km SM-SF coil. At the end of the optical link, the signal is injected to a fast photo-detector (Miteq, model DR-125G-A), and its electrical output is then amplified and launched to an electrical mixer (mixer 2) in order to demodulate the TV-signal. Finally, by using another power divider, the recovered analog TV-signal could be launched to a digital oscilloscope, on a conventional TV receiver, or to the electrical spectrum analyzer in order to evaluate the quality of the recovered signal. Fig. 6(a) shows the measured electrical spectrum of the transmitted and recovered TV-signal where the signal–noise-ratio (SNR) is 34 dB. Under a procedure as previously described but selecting now a microwave signal of 6.86 GHz, we have obtained the graphs illustrated on Fig. 6(b) that correspond to the transmitted and recovered TV-signal exhibiting a SNR of 31.6 dB.

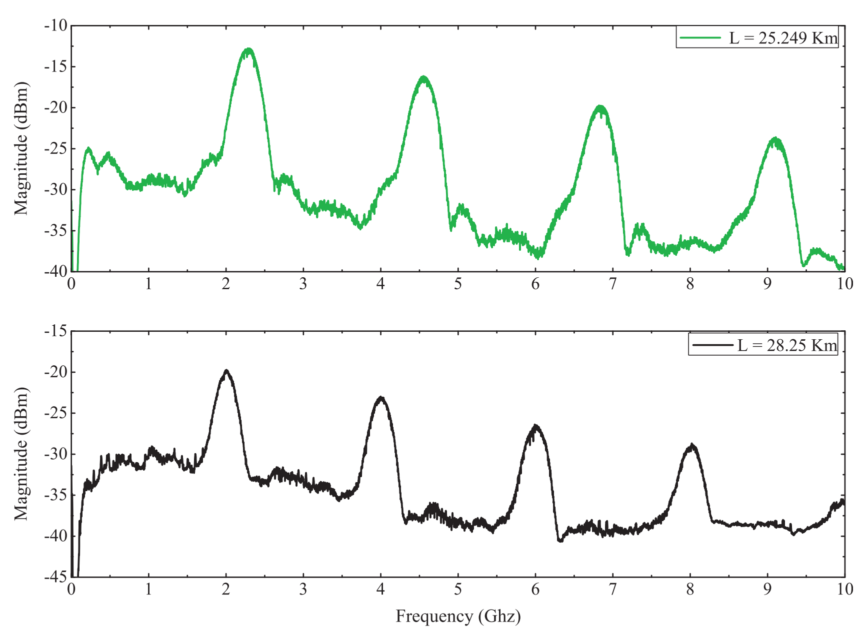

Fig. 4. Experimental frequency response of the filter corresponding to every branch.

Table 1
Location of the theoretical and experimental band-pass windows.

D = 15.81 ps/nm km, dl = 1.1 nm	L = 25.24-km			L = 28.25-km		
Frequency (GHz)	Theoretical	Experimental	% error	Theoretical	Experimental	% error
f_1	2.27	2.31	1.762	2.03	2.01	0.985
f_2	4.54	4.62	1.762	4.06	4.01	1.231
f_3	6.81	6.86	0.734	6.09	6.03	0.985
f_4	9.08	9.14	0.660	8.09	8.05	0.494

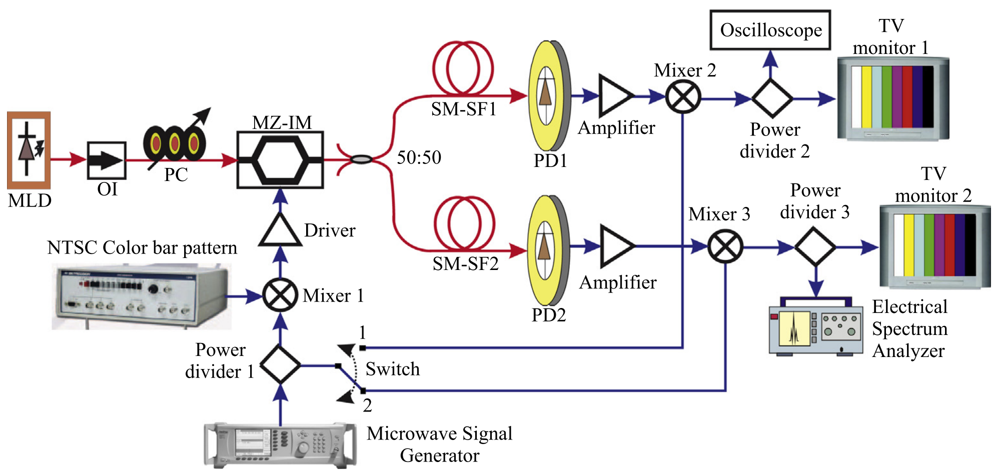

Fig. 5. Experimental setup for TV-signal transmission.

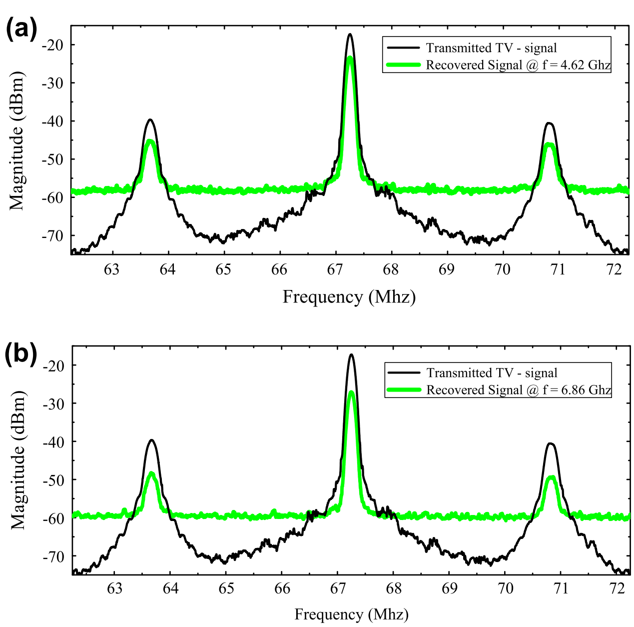

Fig. 6. (a) Electrical spectrums for the transmitted and recovered TV-signal using the band-pass window of 4.62 GHz, (b) Electrical spectrums for the transmitted and recovered TV-signal using the band-pass window of 6.86 GHz.

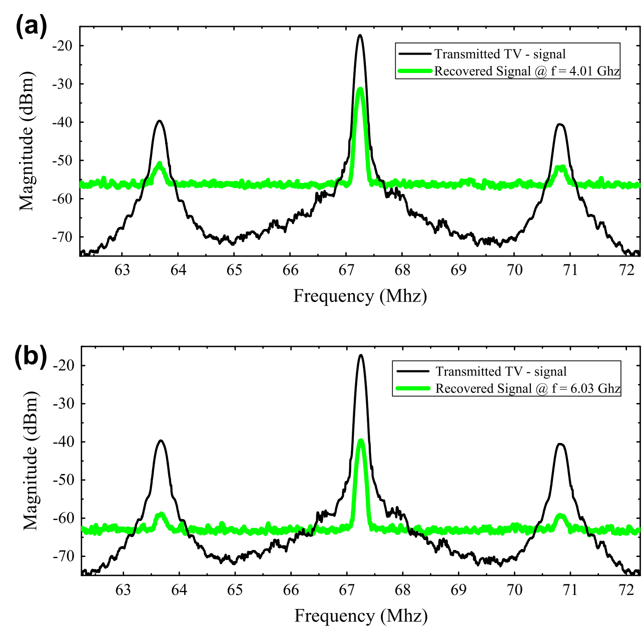

Fig. 7. (a) Electrical spectrums for the transmitted and recovered TV-signal using the band-pass window of 4.01 GHz, (b) Electrical spectrums for the transmitted and recovered TV-signal using the band-pass window of 6.03 GHz.

3.2.2. Experimental transmission of TV-signal using Branch 2

As established at the beginning of this section, using Branch 2 implies the utilization of the band-pass windows located at 4.01 and 6.03 GHz. According to the setup illustrated in Fig. 5, now the switch is placed at position 2. Under a similar procedure previously described in the preceding sub-section, we have obtained the result illustrated in Fig 7(a) that corresponds to the measured electrical spectrum related to the transmitted and recovered TV-signal at 4.01 GHz where the signal–noise-ratio (SNR) is 25.06 dB. Fig. 7(b) illustrates the electrical spectrum that corresponds to the transmitted and recovered TV-signal at 6.03 GHz exhibiting a SNR of 22.54 dB. SNR values are in the range of acceptable noise figures for optical links (24–50 dB) [11]. Fig. 8(a) shows a screen of the oscilloscope where upper and lower traces are the time domain waveforms of standard NTSC composite color video signal corresponding to the transmitted and recuperated signals using

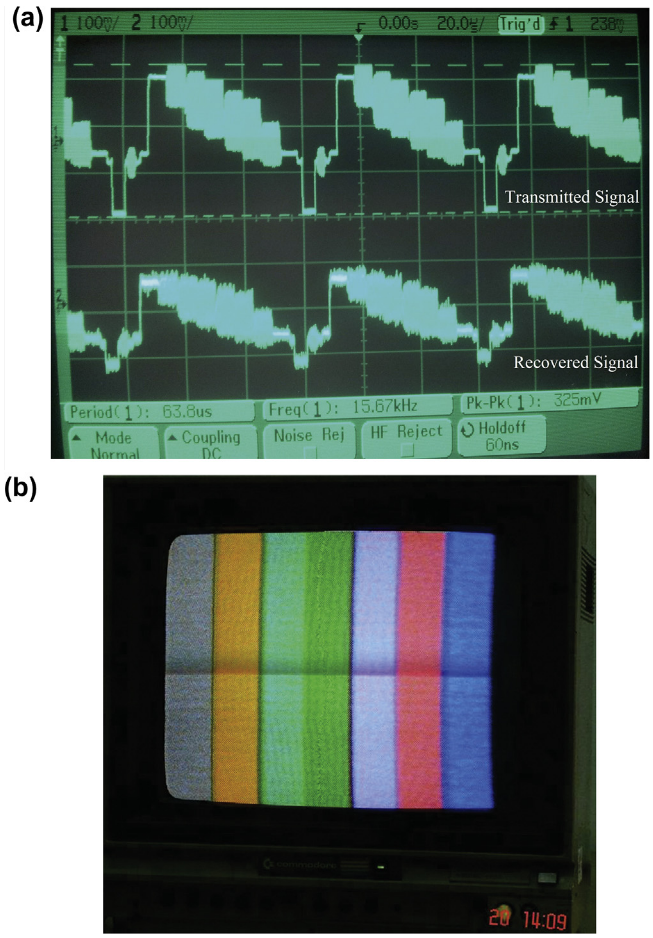

Fig. 8. (a) Time domain waveforms of standard composite color video signal, (b) Recovered NTSC color bar pattern.

the band-pass window of 4.62 GHz. Finally, Fig. 8(b) corresponds to a picture of the screen of the TV-monitor showing that the signal was recovered without noticeable degradation.

4. Conclusion

We successfully demonstrated an electro-optical transmission system for distribution of video over long-haul optical point-to-point links using a microwave photonic filter (MPF) in the frequency range of 0.01–10 GHz. A mathematical analysis corresponding to the microwave photonic filter was described demonstrating that the frequency response of the MPF is proportional to the Fourier transform of the spectrum of the optical source used. The proposed MPF represents an interesting technological alternative for transmitting information by using optoelectronic techniques. For this goal, we have conducted a series of experiments in order to validate the proposal. Filtering of microwave signal was achieved through the appropriate use of the chromatic fiber dispersion parameter, the physical length of the optical fiber, and the free spectral value of the multimode laser. Furthermore, this MPF was used successfully to transmit analog NTSC TV-signal coded on microwave band-passes located at 4.62, 6.86, and 4.0 and 6.0 GHz over long-haul optical links of 25.25 km and 28.25 km, respectively. It is very important to remark the usefulness of the chromatic dispersion parameter of the optical fiber to obtain filtering of microwave signals. Experimentally, the presence of four band-pass windows on the frequency response of the MPF was consequence of the bandwidth of 12 GHz of the photo-detector used. Due to technical limitations (bandwidths of mixers and power dividers), the band-pass windows placed at 8.05 GHz and 9.14 GHz were not used. Finally, we highlight the advantage of the proposed filter that consists of a very simple structure with the use of only one optical source to feed the two branches. The proposed scheme is a suitable candidate for FTTH network architectures.

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