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LETTER

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Experimental transmission in a fiber-radio system using a microwave photonic filter at 2.8 GHz

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Abstract: This paper deals with the experimental transmission of analog TV-signal in a fiber-radio scheme using a microwave photonic filter. For that purpose, filtering of a microwave band-pass window located at 2.8 GHz is obtained by the interaction of an externally modulated multimode laser diode emitting at 1.5 μm associated to the chromatic dispersion parameter of an optical fiber. Transmission of TV-signal coded on the microwave band-pass window is achieved over an optical link of 20.70 Km. Demodulated signal is transmitted via radiofrequency using printed antennas. This communication scheme has a potential application in the field of FTTx network architectures.

Keywords: hybrid fiber-radio system, microwave photonic filter, multimode laser diode, chromatic dispersion

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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1 Introduction

Currently, microwave photonics, which brings together radiofrequency engineering and optoelectronics, has attracted great interest in the field of telecommunications since it is an excellent alternative for the transmission of services such as high quality audio and video, e-mail, and Internet among others [1]. Another interesting application that attracts interest in research is the filtering of microwave signals by using photonic techniques. The main feature of a photonic filter is that microwave signals are directly processed in the optical domain exploiting advantages inherent to photonics such as low loss, high bandwidth, immunity to electromagnetic interference, and tunability [2]. On the other hand, network architectures such as FTTx, where x can stand for home (H), building (B), neighborhood (N), or curb (C), are a communication architecture in which the final connection to the subscribers is optical fiber [3]. Another important application of photonic telecommunications systems, which is very closely related to the FTTx systems, is the distribution of signals for being transmitted in wireless networks by integrating optical and wireless networks. This particular type of scheme is referred to as fiber-radio system [4]. In this sense, the aim of this paper is to show how using a microwave photonic filter can contribute to the field of fiber-radio systems. The significant relevance of this work resides in the proper use of the chromatic dispersion parameter of the optical fibers to obtain filtered signals. In this paper we describe an experimental transmission of analog TV-signal coded in a filtered microwave band-pass window located at 2.8 GHz that is obtained by the interaction of an externally modulated multimode laser diode emitting at 1.5 μm associated to the chromatic dispersion parameter of an

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optical fiber. Transmission of TV-signal is achieved over an optical link of 20.70-Km, whereas a demodulated signal is transmitted via radiofrequency using printed antennas.

2 Analytical model of the microwave photonic filter

Fig. 1 shows the basic topology of the microwave photonic filter (MPF) used in this work. In the following, we describe in summary its operating principle [5].

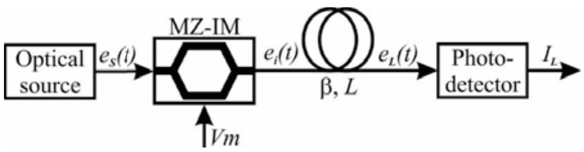

Fig. 1. Basic topology of the microwave photonic filter

In a first step, the optical source is assumed to be quasi-monochromatic with spectrum $S_0(\omega-\omega_0)$, centered at an optical frequency ω_0. Such a signal has associated an analytical signal which can be modeled by a stochastic process $e_s(t) = e_0(t)e^{(j\omega_0 t)}$, where $e_0(t)$ is the complex envelope. If its intensity is modulated by a Mach-Zehnder Intensity Modulator (MZ-IM) operated on the linear region with an electric signal $V_m = 1 + 2mcos(\omega_m t)$ of electrical frequency ω_m, then, the optical field at the input of the optical fiber is given as [6]

$$e_i(t) = e_s(t)\left[1 + \frac{1}{2}me^{j\omega_m t} + \frac{1}{2}me^{-j\omega_m t}\right] \tag{1}$$

The modulation index m, is related to the electrical input signal amplitude, V_m by $2m = \pi(V_m/V_\pi)$, where V_π is 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), the optical field at the output of the optical fiber, denoted as $e_L(t)$, is given by the convolution of $e_i(t)$ with the impulse-response function $h(t)$ of the system, i.e. $e_L(t) = e_i(t) * h(t)$. In the frequency domain the impulse-response function for a given length L is $H(\omega) = e^{-j\beta L}$. Thus, applying the convolution theorem, the optical field at the output of the optical fiber is

$$E_L(\omega) = E_i(\omega)H(\omega) = E_i(\omega)e^{-j\beta L} \tag{2}$$

where $E_L(\omega)$ and $E_i(\omega)$ are the Fourier transforms of $e_L(t)$ and $e_i(t)$, respectively. By developing Eq. (2), it becomes

$$\begin{aligned} E_L(\omega) = e^{-j\beta L}\Big\{ & E_0(\omega-\omega_0) \\ & + \frac{m}{2}[E_0(\omega-(\omega_0-\omega_m)) + E_0(\omega-(\omega_0+\omega_m))]\Big\} \end{aligned} \tag{3}$$

where $E_0(\omega)$ is the Fourier transform of $e_0(t)$. Eq. (3) contains three wave-packets centered at different frequencies; therefore, in the presence of chro-

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matic dispersion, each wave-packet experiences a different propagation constant, i.e. $\beta(\omega - \omega_0)$, $\beta(\omega - (\omega_0 - \omega_m))$, and $\beta(\omega - (\omega_0 + \omega_m))$. Assuming that within the frequency range $\Delta\omega = 2\omega_m$, centered at ω_0, β varies slightly and gradually with ω, then, it can be approximated by the first three terms of a Taylor series expansion in the neighborhood of ω_0, i.e. $\beta(\omega-\omega_0) = \beta_0+\beta_1(\omega-\omega_0)+\frac{1}{2}\beta_2(\omega-\omega_0)^2$. Where $\beta_i = [d^i\beta(\omega)/d\omega^i]_{\omega=\omega_0}$. For simplicity, the linear phase shift β_0 and the fiber-induced group delay β_1 are omitted, then this last expression takes the form [7] $\beta(\omega-\omega_0) = \frac{1}{2}\beta_2(\omega-\omega_0)^2$. In this way

$$\beta(\omega - \omega_0 \pm \omega_m) = \frac{1}{2}\beta_2[((\omega - \omega_0)^2 + \omega_m^2) \pm 2\omega_m(\omega - \omega_0)] \tag{4}$$

Because $\omega_0 \gg \omega_m$, then, $E_0(\omega - \omega_0) \approx E_0(\omega - \omega_0 + \omega_m) \approx E_0(\omega - \omega_0 - \omega_m)$. Furthermore, by the Wiener–Khinchin theorem [8], the spectrum is defined as the Fourier transform of the temporal coherence function Γ_L i.e.

$$S_L(\omega) = \int_{-\infty}^{\infty} \Gamma_L(\tau) exp(-j\omega\tau)d\tau$$

where $\Gamma_L(\tau) = \langle e_L(t)e_L^*(t+\tau)\rangle$. But by the correlation theorem $F.T.\{\Gamma_L(\tau)\} = E_L(\omega)E_L^*(\omega)$, $F.T.\{\quad\}$ stands for Fourier transform. In addition, it is assumed the MZ-IM operates on the linear region, then, $m^2 \approx 0$. Thus substituting Eq. (4) in Eq. (3), the spectral density at the end of the optical fiber is

$$\begin{aligned} S_L(\omega) &= S_0(\omega - \omega_0) \\ &\quad + 2mS_0(\omega - \omega_0) cos\left(\frac{1}{2}\omega_m^2\beta_2 L\right) cos(\omega - \omega_0)\omega_m\beta_2 L \end{aligned} \tag{5}$$

where $S_0(\omega - \omega_0) = E_0(\omega - \omega_0)E_0^*(\omega - \omega_0)$ is the spectral density of the optical source. The total average intensity at the end of the optical fiber is found by integrating S_L over the positive frequencies [9], i.e.

$$I_L = \int_0^{\infty} S_L(\omega)d\omega \tag{6}$$

Replacing Eq. (5) in Eq. (6), this can be written as

$$\begin{aligned} I_L = &\int_0^{\infty} S_0(\omega - \omega_0)d\omega + 2m cos\left(\frac{1}{2}\omega_m^2\beta_2 L\right) \\ &\cdot \int_0^{\infty} S_0(\omega - \omega_0) cos((\omega - \omega_0)\omega_m\beta_2 L)d\omega \end{aligned} \tag{7}$$

The first integral in Eq. (7) corresponds to the average intensity due to the optical source I_0. By defining $W = \omega - \omega_0$, with $dW = d\omega$, and its reciprocal $Z = \omega_m\beta_2 L$, Eq. (7) becomes

$$I_L = I_0 + m cos\left(\frac{1}{2}\omega_m^2\beta_2 L\right) \cdot 2\int_0^{\infty} S(W) cos(WZ)dW \tag{8}$$

Because I_L and $S(W)$ are real functions. Then, the result of the integral in Eq. (8) must also be real. If a given function $f(t)$ is real and its Fourier transform $F(\omega)$ is also real, then $F(\omega)$ can be obtained from [10]

$$F(\omega) = 2\int_0^{\infty} f(t) cos(\omega t)dt$$

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This is, the integral in Eq. (8) has the same form as the Fourier transform of $S(W)$. Furthermore, it is possible to demonstrate that $\beta_2 = -D(\lambda^2/2\pi c)$, where λ is the wavelength, D is the chromatic dispersion parameter of the 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. (8) can be written as

$$I_L = I_0 + m\cos\left(\frac{1}{4\pi c}\omega_m^2\lambda^2 DL\right) F.T.\{S(W)\} \tag{9}$$

In summary, it has been demonstrated that the frequency response of the microwave photonic filter is determined by the second term of Eq. (9), which is proportional to the Fourier transform of the spectrum of the optical source used.

3 Influence of an optical source with a multimode spectrum over the frequency response of the microwave photonic filter

A multimode laser diode exhibiting a Gaussian envelope and modes centered at an angular frequency ω_0 is modeled as [11]

$$\begin{aligned} S(W) = {} & \frac{2S_0}{\Delta_\omega\sqrt{\pi}} exp\left(-\frac{4(\omega-\omega_0)^2}{\Delta_\omega^2}\right) \\ & \cdot \left[\frac{2}{\sigma_\omega\sqrt{\pi}} exp\left(-\frac{4(\omega-\omega_0)^2}{\sigma_\omega^2}\right) * \sum_{n=-\infty}^{\infty}\delta(\omega - n\delta_\omega)\right] \end{aligned} \tag{10}$$

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 earlier, the Fourier transform of Eq. (10) is

$$\begin{aligned} F.T.\{S(\omega)\} = {} & exp\left(-\left(\frac{\Delta_\omega Z}{4}\right)^2\right) \\ & * \left[exp\left(-\left(\frac{\sigma_\omega Z}{4}\right)^2\right) \cdot \left(\frac{1}{\delta_\omega}\sum_{n=-\infty}^{\infty}\delta\left(Z - n\frac{2\pi}{\delta_\omega}\right)\right)\right] \end{aligned} \tag{11}$$

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

$$f_n = \frac{n}{DL\delta_\lambda} \tag{12}$$

where n is a positive integer ($n = 1, 2, \ldots$), D is the chromatic dispersion parameter, L is the length of the optical fiber and δ_λ is the FSR of the spectrum given in nm. It is very important to remark that this periodic pattern appears only if the spectrum of the optical source is of multimode

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type. The first term of Eq. (10), allows us to determine the low-pass band of the MPF, and so, the Fourier transform corresponding to this term is

$$F.T.\{S(\omega)\} = exp\left[-\left(\frac{\Delta_\omega \omega_m \beta_2 L}{4}\right)^2\right] \tag{13}$$

This is also a Gaussian function. Equating (13) with $S(\omega) = \ln 2$

$$-\left(\frac{\Delta_\omega \omega_m \beta_2 L}{4}\right)^2 = ln2 \tag{14}$$

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

$$d\omega = -\frac{2\pi c}{\lambda^2} d\lambda \Leftrightarrow \Delta\omega = -\frac{2\pi c}{\lambda^2}\Delta\lambda \tag{15}$$

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 $\beta_2 = -D(\lambda^2/2\pi c)$. Finally, by substituting $\omega_m = 2\pi f_m$, Δ_ω, as defined in Eq. (15), and the expression for β_2 in Eq. (14), the frequency f_m, corresponds to the low-pass frequency response of the MPF Δf_{lp} that can be expressed as

$$\Delta f_{lp} = -\frac{2\sqrt{ln2}}{\pi D L \Delta\lambda} \tag{16}$$

In order to determine the bandwidth of each band-pass window, it is necessary to consider the double of Eq. (16), i.e. the corresponding bandwidth at -3 dB of the nth band-pass window is given as

$$\Delta f_{bp} = -\frac{4\sqrt{ln2}}{\pi D L \Delta\lambda} \tag{17}$$

In summary, it has been demonstrated that the frequency response MPF includes a low-pass band centered at zero frequency and multiple band-pass windows that depend on the spectral characteristics of the multimode laser diode and on the chromatic dispersion value of the optical fiber, as well as on its length.

4 Experimental setup of optical and wireless transmission

In a first step, the multimode laser diode (MLD) used in this experiment (OKI OL5200N-5) is optically characterized by means of an optical spectrum analyzer (Agilent, model 86143B). Fig. 2 corresponds to the measured optical spectrum obtaining $\lambda_0 = 1553.53\,nm$, $\Delta\lambda = 5.65\,nm$, and $\delta\lambda = 1.00\,nm$

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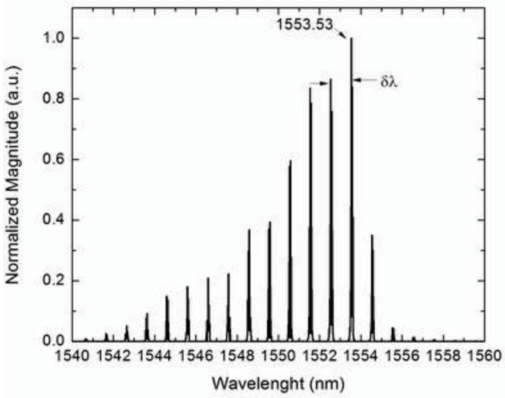

Fig. 2. Optical spectrum for the MLD used in the experiment

for a driver current of 25 mA. 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.

In a second step, considering a length $L = 20.70$-Km of single-mode-standard-fiber (SM-SF) exhibiting a chromatic fiber-dispersion parameter of $D = 16.67$ ps/nm-Km. Eq. (12) allows us to determine the value of the central frequency corresponding to the first filtered microwave or first band-pass as

$$f_1 = \frac{1}{DL\delta_\lambda} = \frac{1}{(16.67 \times 10^{-12}\, seg/nm \cdot Km) \cdot (20.70\, Km) \cdot (1.0\, nm)} = 2.8\, GHz$$

Eq. (16) permits us to determine the value of the low-pass band as

$$\Delta f_{lp} = \frac{2\sqrt{ln2}}{\pi DL\Delta\lambda} = \frac{2\sqrt{ln2}}{(\pi)(16.67 \times 10^{-12}\, seg/nm \cdot Km) \cdot (20.70\, Km) \cdot (5.65\, nm)} = 271.85\, MHz$$

Finally, according to Eq. (17), the corresponding bandwidth of the band-pass window is $\Delta f_{bp} = 543.70\, MHz$.

At this point, it is well worth highlighting the advantageous use of the chromatic dispersion parameter to obtain the filtered microwave signal. Once the main parameters are known, the topology illustrated in Fig. 3 is assembled in order to evaluate the frequency response of the MPF.

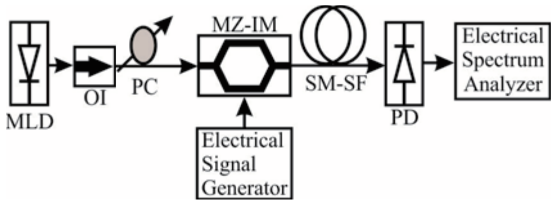

Fig. 3. Experimental microwave photonic filter

At the output of the MLD, an optical isolator (OI) is placed in order to avoid reflections to the optical source. Since the MZ-IM (Photline MX-LN-10) is polarization-sensitive, a polarization controller (PC) is used to

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maximize the modulator output power. The optical signal is launched into the MZ-IM. The microwave electrical signal (RF) for modulating the optical intensity is supplied by an electrical signal generator (Anritsu, model MG3692C) in the frequency range of 0.01–4 GHz at 0 dBm. The intensity-modulated optical signal is then coupled into a 20.70-Km of SM-SF coil. The length of the optical fiber is corroborated by using an optical time domain reflectometer, OTDR (EXFO, model FTB-7300E). At the end of the link, the optical signal is applied to a fast Photo-Detector (PD, Miteq DR-125G-A), and its output connected to an electrical spectrum analyzer (Anritsu, model MS2830A-044), in order to measure the frequency response of the MPF. Fig. 4 corresponds to the measured experimental frequency response where a low-pass band centered at zero frequency and the presence of a band-pass band centered at 2.8 GHz are clearly appreciable.

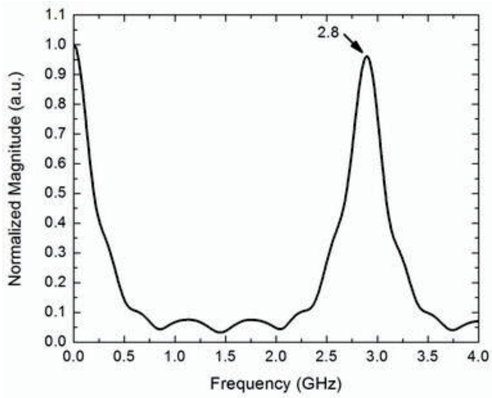

Fig. 4. Experimental frequency response of the filter

The bandwidth of 543.70 MHz associated to the band-pass window centered at 2.8 GHz allows us to guarantee enough bandwidth in case of fluctuations (in the order of nanometers) between mode spacing. On the other hand, a considerable increase on the length of the optical fiber due to thermal expansion is practically impossible. These considerations permit us to guarantee a good stability for the microwave photonic filter.

Once the frequency response of the MPF is determined, the setup illustrated in Fig. 5 is assembled for carrying out the fiber-radio transmission.

Now, the electrical signal generator provides a signal of 2.8 GHz at 0 dBm that is used as the electrical carrier and demodulated signal. This signal is separated by using a power divider. Part of this signal is transmitted via radio frequency by the antenna, and the rest is mixed with an analog NTSC (National Television System Comittee) TV-signal of 67.25 MHz. 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 20.70-Km SM-SF coil. At the end of the optical link, the signal is injected to a fast photo-detector, and its electrical output is then amplified and launched to an electrical mixer. Another patch antenna placed at a distance of 10 meters is connected to a port of the mixer in order to recuperate

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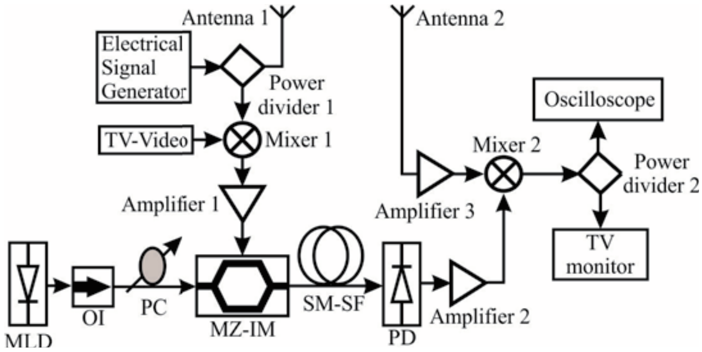
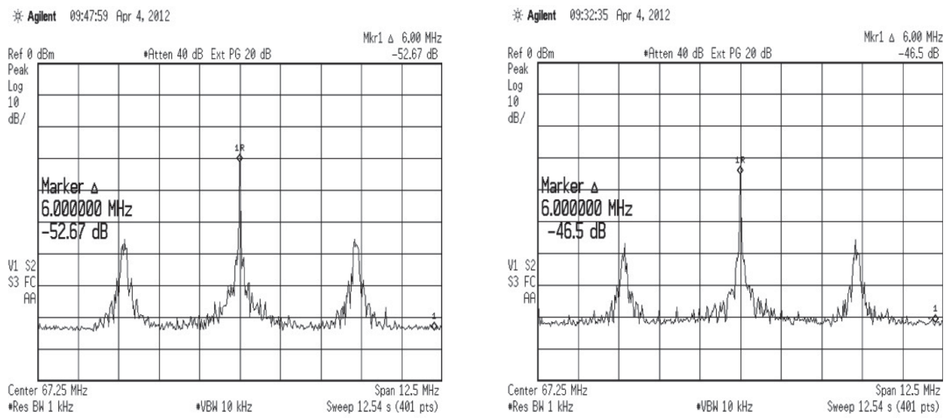


Fig. 5. Experimental setup for optical and wireless transmission

the microwave signal that plays the role of the demodulated signal. Finally, by using another power divider, recovered analog TV-signal can be launched to a digital oscilloscope or to the electrical spectrum analyzer in order to evaluate the quality of the recovered signal and at the same time display the TV-signal on a TV-monitor. Fig. 6 (a) shows the measured electrical spectrum (Agilent, E4407B) corresponding to the transmitted TV-signal where the signal-noise-ratio (SNR) is 52.67 dB, whereas Fig. 6 (b) corresponds to the recovered TV-signal with a SNR of 46.5 dB. Finally, Fig. 7 corresponds



(a) (b)

Fig. 6. Electrical Spectrums for (a) Transmitted and (b) recovered TV-signal

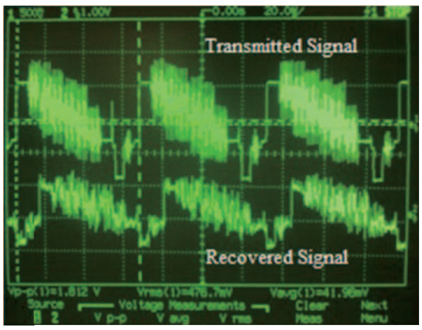


Fig. 7. Transmitted and recovered TV-signal

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to a photograph of the screen of the oscilloscope where upper and lower traces are the waveforms of the transmitted and recuperated signal, respectively.

5 Conclusion

In this paper we have described a novel fiber-radio scheme to transmit an analog NTSC TV-signal coded on a microwave band-pass located at 2.8 GHz. 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. Transmission of a TV-signal was achieved over an optical link of 20.70 Km, whereas a demodulated signal was transmitted via radiofrequency using patch antennas. Although the distance between antennas was short, this distance can be lengthened if an array of antennas is used. A mathematical analysis corresponding to the microwave photonic filter was described demonstrating that the frequency response of the microwave photonic filter is proportional to the Fourier transform of the spectrum of the optical source used. The proposed microwave photonic filter represents an interesting technological alternative for transmitting information by using optoelectronic techniques. To the best of our knowledge this is the first time that a microwave photonic filter is used in conjunction with a radiofrequency scheme. We have conducted a series of experiments in order to validate the proposal. The results here reported open the possibility of transmitting analog or digital information coded on some band-pass. The optical and electric characteristics obtained make the proposed fiber-radio scheme a suitable candidate for FTTx network architectures. With the fact that the location of the band-pass window present in the frequency response of the MPF is fixed at a particular length of optical fiber, a potential application using this “disadvantage”, could be exploited if at the end of the optical link the information is radiated by an antenna and distributed to users located in geographic locations with difficult access. This particular type of scheme is precisely referred as a fiber-radio system [4]. Finally, it is well worth highlighting the tunability of the microwave photonic filter. This tunability can be achieved by varying the optical fiber length, or adjusting the free spectral range (FSR) between the modes of the optical source by using a Fabry-Perot filter. Currently, this experiment is being conducted by the authors.

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