transmission zeros to improve the selectivity in the similar filter design.

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RECONFIGURING THE FREQUENCY RESPONSE OF DISPERSIVE-CHANNEL RADIO OVER FIBER SYSTEMS BY USING FIBER PHOTONIC FILTERS: APPLICATION TO TRANSMISSION OF MULTIPLEXED MICROWAVE SUBCARRIERS

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ABSTRACT: *Radio over fiber schemes using multimode lasers and dispersive optical channel show a periodic band-pass microwave frequency response. Such a response can be used for implementing photonic microwave filters or for multiplexing modulated microwave subcarriers. The reconfiguration of the frequency response using optical retarders acting as photonic filters is demonstrated in this article. The multiplexed transmission of two data-modulated microwave subcarriers on two adjacent transmission windows is also described.* © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 54:1869–1874, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26972

Key words: *multimode lasers; fiber optics dispersion; photonic filters; optical delays; radio over fiber; microwaves; electro-optic modulators*

1. INTRODUCTION

Radio over fiber systems, using broadband optical sources and a dispersive optical media, can be potentially used either for implementing photonic microwave filters or for transmitting modulated microwave subcarriers for high-speed telecommunications.

The association of a dispersive propagation media and a multimode optical spectrum gives a periodic band-pass microwave response. A broadband optical spectrum can be realized using sets of tunable lasers (TLs), optically filtering the spectrum of erbium-doped fiber amplifiers (EDFA), or using semiconductor multimode lasers diodes (MMLD). The dispersive media can be a standard single-mode optical fibers (SSMF), fiber Bragg gratings (FBG), or arrayed waveguide gratings. As an application of the association of a broadband optical spectrum and dispersive media, photonic microwave filters are being studied, aiming to show potential applications on radio over fiber systems and in high-speed signal processing [1–5]. The use of periodic band-pass response, for transmitting multiplexed microwave subcarriers, has been previously described [6, 7]. An important issue, related to the dispersive media-broadband optical source schemes, is the reconfiguration and tunability of the microwave frequency response. Many papers report on the tunability of the frequency response [7–14]. Most of these works are based on a set of TLs and either standard optical fibers [8] or fiber Brag gratings [9–11], as the dispersive media. When using TLs and FBG, the schemes become relatively complex, as many TLs are required. Additionally other optical components as directional couplers, attenuators, power splitters, optical circulators, are necessary.

Simpler schemes, using a unique optical source, have been also proposed. Reconfiguration is obtained using a broadband amplified spontaneous emission from EDFA's and delay lines [12]. In the work reported in Ref. 13, the reconfiguration is based on the shaping of the emission from an EDFA by a dynamic gain equalizer; this shaping is followed by an optical filtering or slicing. A simple scheme describes the reconfiguration as based on varying the injection current on a multimode Fabry-Pérot laser [14].

The work described in this article is as simple as the scheme in Ref. 14. However, in our case, the frequency response is reconfigured by filtering the optical spectrum as to increase the free spectral range (FSR). This approach is simpler to implement, as the optical spectrum can be modified by an optical retarder, acting as photonic filter. The photonic filter introduces an optical delay, or its equivalent optical path-difference (OPD), which corresponds to a filtering function in the spectral domain [15, 16]. The photonic filter can be matched to the optical spectrum for achieving a selective elimination of optical modes thus increasing the FSR. In this way, the position and number of the band-pass transmission windows in the electrical frequency response can be reconfigured. In the first part of this article, we briefly recall the model of the frequency response of a radio over fiber scheme using a multimode laser and a dispersive optical fiber channel. The frequency response of a scheme associating a 0.5 nm FSR multimode laser and a 25 km dispersive optical fiber channel, shows band-pass microwave transmission windows centered at 0, 4, 8,.....GHz. This frequency response can be modified by OPD's, which filter the optical spectrum and in this way, the electrical microwave response is reconfigured. When the 0.5 nm FSR optical spectrum is filtered by an OPD of 2.2 mm, the FSR is increased to 1 nm and the frequency response will show transmission windows at 0, 2, 4, 6, 8,......GHz. If an OPD of 1.48 mm is used, the FSR is increased to 1.5 nm and the frequency response shows band-pass windows centered at 0, 1, 2, 3, 4,.......GHz. The filtering process is described and demonstrated.

In the second part of this article, as an illustrative potential application of the optical filtering process, we describe the experimental multiplexed transmission of two data-modulated microwave subcarriers centered at 7 and 8 GHz, which result when an OPD of 1.48 mm has been used to filter the multimode laser spectrum. The multiplexed transmission-reception process is demonstrated, showing the self-filtering effect as given by the dispersive channel radio over fiber scheme. At the output of the optical receiver, the modulated subcarriers are detected by homodyne mixing and the base-band data is recuperated. No evaluation of the data transmission parameters (signal to noise ratio [SNR], bit error rate [BER], power penalty, etc.) is given as this aspect is beyond the scope of this article.

2. MICROWAVE BAND-PASS TRANSMISSION WINDOWS

Periodic band-pass microwave transmission windows, on radio over fiber schemes, result from the association of a multimode laser and a dispersive optical fiber channel. The frequency response of such a scheme is determined by the spectral characteristics of the optical source and by the length of the dispersive optical channel. The detailed model has been previously reported [6]. To recall the operating principle and the corresponding model, the basic scheme is presented in Figure 1. In the model, the optical source is represented by a complex random process $s(t) = c(t)\, e^{j\Omega o t}$ with optical spectrum $P(\Omega)$, Ω is the optical frequency. The transfer function of the optical channel is given as $h_f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-j\beta(\Omega)z}\, e^{j\Omega t}\, d\Omega$. To account for chromatic dispersion, the propagation constant can be expressed as $\beta(\Omega) = \beta_0 + \beta_1(\Omega - \Omega_0) + \frac{1}{2}\beta_2(\Omega - \Omega_0)^2$.

As detailed elsewhere [6], if the light is intensity modulated by a signal $m(t) = 1 + 4m_0\cos(\omega_m t)$, after transmission through

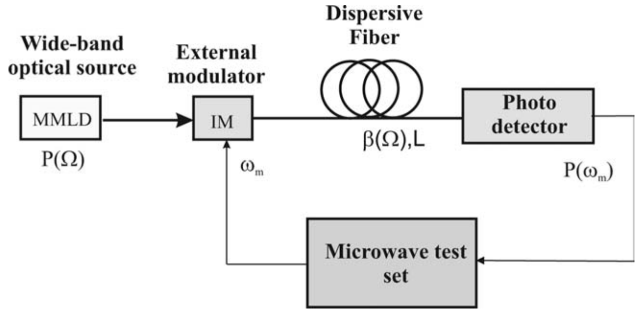

Figure 1 Broad-band optical spectrum and dispersive-optical channel radio over fiber scheme

the optical channel of length z, the received average optical power is given as

$$P(t,\omega_m,z) = \frac{1}{2\pi}\int P(\Omega)d\Omega + 2m_0\cos\left(\frac{\omega_m^2}{2}\beta_2 z\right) \times \cos(\omega_m t + \omega_m\beta_1 z) \times \mathrm{Re}\left[\int P(\Omega)\, e^{-j(\omega_m\beta_2 z(\Omega-\Omega_0))}\, d\Omega\right] \quad (1)$$

As given by eq. (1), the optical power depends basically on the real part of the Fourier transform of the optical spectrum. If the optical source is a Gaussian-envelope, multimode laser diode, Figure 2(a), its optical spectrum is given as

$$P(\Omega) = P_0\exp\left(\frac{4(\Omega-\Omega_0)^2}{\Delta\Omega^2}\right)\left[\exp\left(\frac{4\Omega^2}{d\Omega^2}\right)\otimes\sum_{n=-\infty}^{\infty}\delta(\Omega - n\delta\Omega)\right]$$

where Ω_0 is the center optical frequency; $\Delta\Omega$ is the envelope optical bandwidth; $d\Omega$ is the FWHM of each optical mode and δ_Ω is the FSR.

From Eq. (1), the frequency response of the multimode laser emission-dispersive optical channel, is proportional to

$$P(\omega_m,z)\alpha A_0\left[\exp\left(-\left(\frac{\Delta_\Omega\,\omega_m\,\beta_2\,z}{4}\right)^2\right)\otimes\sum_{-\infty}^{\infty}\delta\left(\omega_m\,\beta_2\,z - \frac{2\pi n}{\delta_\Omega}\right)\right] \quad (2)$$

The resulting frequency response shows a low-pass window and series of band-pass windows, centered at $f_n = \frac{n}{DL\partial\lambda}$, n is an integer. D is the fiber dispersion parameter, L is the optical fiber length. $\Delta\lambda$ is the envelope optical bandwidth and $\partial\lambda$is the FSR in wavelengths. The frequency response of the scheme was simulated for the Gaussian multimode laser and dispersive optical channel (25 km SSMF). The spectral parameters of the laser are: center wavelength, $\lambda_0 = 1549$ nm; envelope spectral width, $\Delta\lambda = 6$ nm; FSR, $\delta\lambda = 0.5$ nm; mode FWHM, $d\lambda = 0.2$ nm. Such parameters correspond to a real multimode laser.

The simulated laser spectrum is shown in Figure 2(a). To calculate the electrical frequency response, the laser light is externally modulated in a 0–20 GHz frequency range. Figure 2(b) shows the expected theoretical microwave response. The frequency response exhibits band-pass windows located at 0, 4.2, 8.4, 16.8,...GHz. In a practical approach, this frequency response can be used as band-pass microwave filters or for multiplexing modulated microwave subcarriers that can be allocated in the transmission windows. This second approach is explored in the second part of this article.

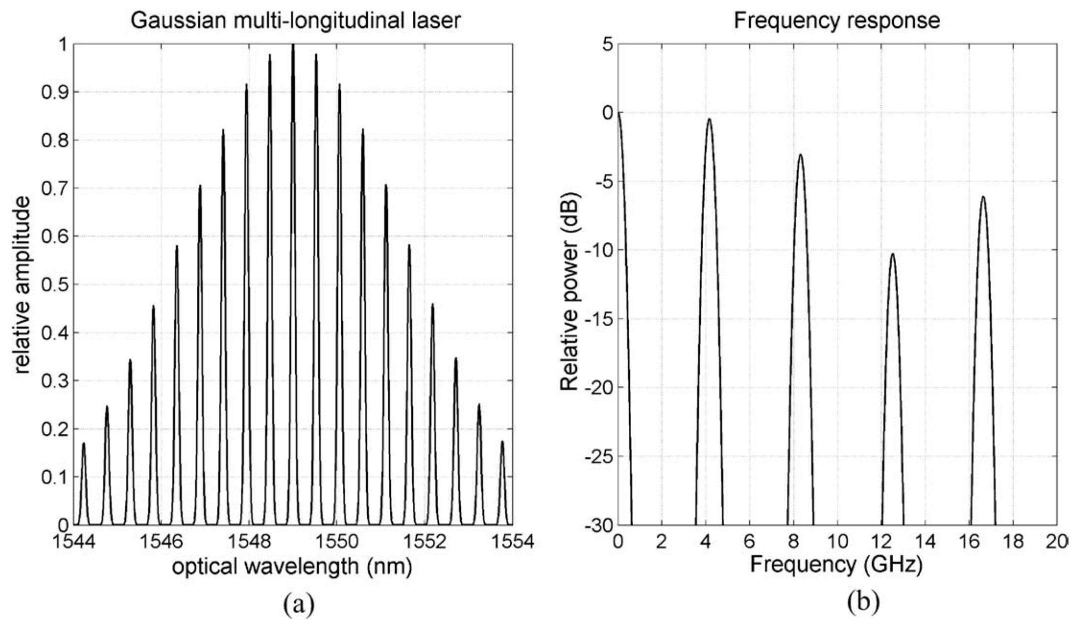

Figure 2 a) Multimode laser spectrum; b) Theoretical microwave frequency response

3. PHOTONIC FILTERING

The frequency response of the system described in the last section can be modified either by changing the length of the optical channel or by modifying the optical spectrum.

The first approach requires additional optical fiber lengths and is not considered in this study. The second approach is more attractive and very simple to implement, as the optical spectrum can be modified using fiber optic photonic filters. A photonic filter is modeled here as an optical retarder which introduces an optical delay or its equivalent OPD, Figure 3(a). An OPD can be easily implemented by birefringent polarization maintaining optical fibers (PMF) or birefringent electro-optic crystals. An OPD ''channelizes'' an optical spectrum and this effect has been described when studying coherence modulation of light [15, 16]. An optical retarder receives an optical signal $s(t)$ and outputs $s_0(t) = \frac{1}{2}s(t) + \frac{1}{2}s(t-\tau)$, $\tau$is the optical delay. In the Fourier domain, the energy spectral density at the output of the optical retarder corresponds to

$$S_0(\lambda) = \frac{1}{2}\left[S^*(\lambda) + S^*(\lambda)\exp\left(j2\pi\frac{c}{\lambda_0}\tau\right)\right] \times \frac{1}{2}\left[S(\lambda) + S(\lambda)\exp\left(-j2\pi\frac{c}{\lambda_0}\tau\right)\right]$$

This expression simplifies to the filtering function as

$$S_0(\lambda) = \frac{1}{2}P(\lambda)\left[1 + \cos(\frac{1}{\lambda_0}2\pi\, d_m)\right] \tag{3}$$

where, $P(\lambda)$ is power spectrum of the optical source and $d_m = c\tau$ is the introduced OPD.

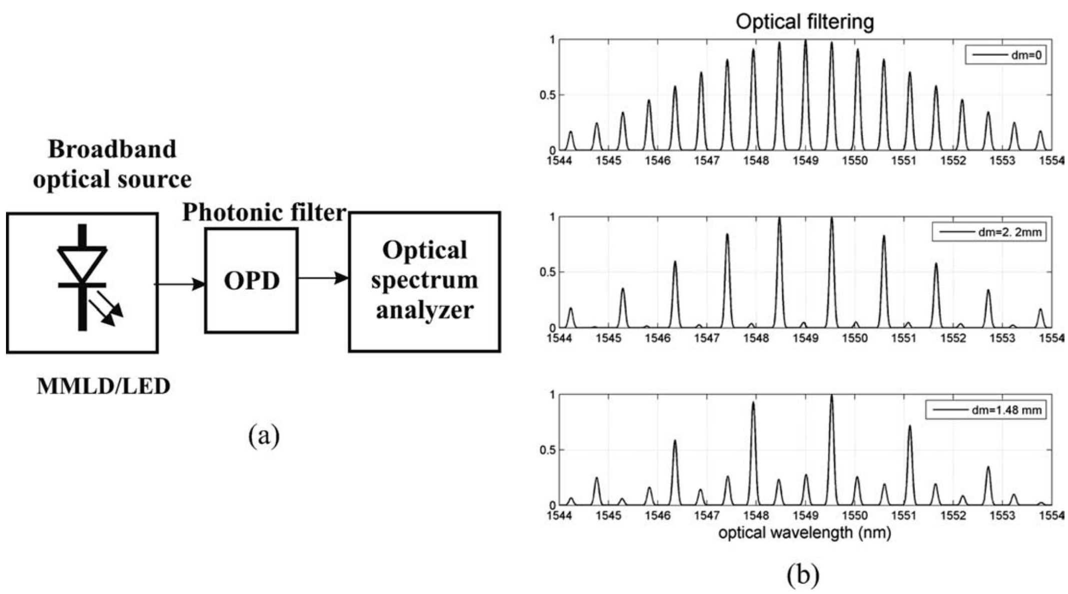

Figure 3 a) A photonic filter scheme; b) theoretical photonic filtering of a laser spectrum

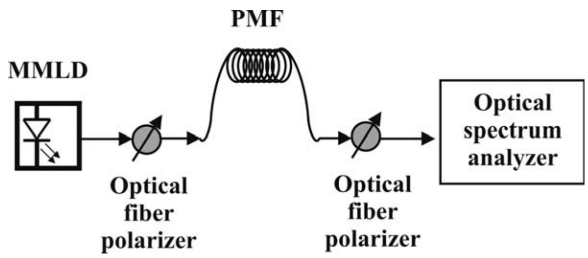

Figure 4 A fiber optics photonic filter

Calculations of different OPD's for filtering the multimode laser were conducted. An optical regular filtering for the cancellation of one or more adjacent optical modes was searched. It was found that OPD's of 2.2 and 1.48 mm matched for a periodic filtering of one and two alternate optical modes in order to increase FSR to 1 and 1.5 nm, respectively. The calculated filtering is depicted in Figure 3(b).

4. EXPERIMENTAL PHOTONIC FILTERING AND RECONFIGURATION OF THE FREQUENCY RESPONSE

The experimental setup for validating the selective optical filtering was based on the scheme of Figure 1, after inserting the fiber photonic filter between the MMLD and an external wideband $LiNbO_3$ Mach-Zehnder electro-optic modulator. In such a setup, a multimode laser emitting in the 1544–1554 nm wavelength range was used.

The optical filtering was achieved using fiber photonic filters, which were implemented by segments of PMF, as shown in Figure 4. The PMF segments were placed between 45° fiber polarizers, to introduce OPDs, whose values were proportional to the fiber birefringence and length. From the simulation results, two segments of PMF for introducing OPD's of 1.48 and 2.2 mm were realized. In Figure 5(a), the unfiltered optical spectrum is shown on the upper graph. The laser exhibits around 18 emission modes with a FSR of 0.5 nm and spectral width of 0.1 nm. In this figure, the experimentally filtered spectra are also shown. The middle graph corresponds to the filtering by an OPD of 2.2 mm; the lower graph corresponds to the filtering by an OPD of 1.48 mm. The measured filtered spectra show excellent agreement to the calculated values from Eq. (3). As can be observed from Figure 5(a), the optical filtering modifies the spectrum increasing the FSRs from 0.5 nm to 1 and 1.5 nm.

After Eq. (1), the modified optical spectra will also modify the microwave frequency response of the dispersive-channel radio over fiber scheme. According to the theoretical model, the new spectra will reconfigure the microwave frequency response and the periodic band-pass windows will be now centered at 2.1•n and 1.05•n GHz, respectively. The microwave frequency responses are shown in Figure 5(b). The upper curve corresponds to the unfiltered spectrum and shows the original microwave response, where the band-pass windows are centered at 4.2•n GHz. The middle curve shows the frequency response for an OPD of 2.2 mm. This frequency response shows new bands

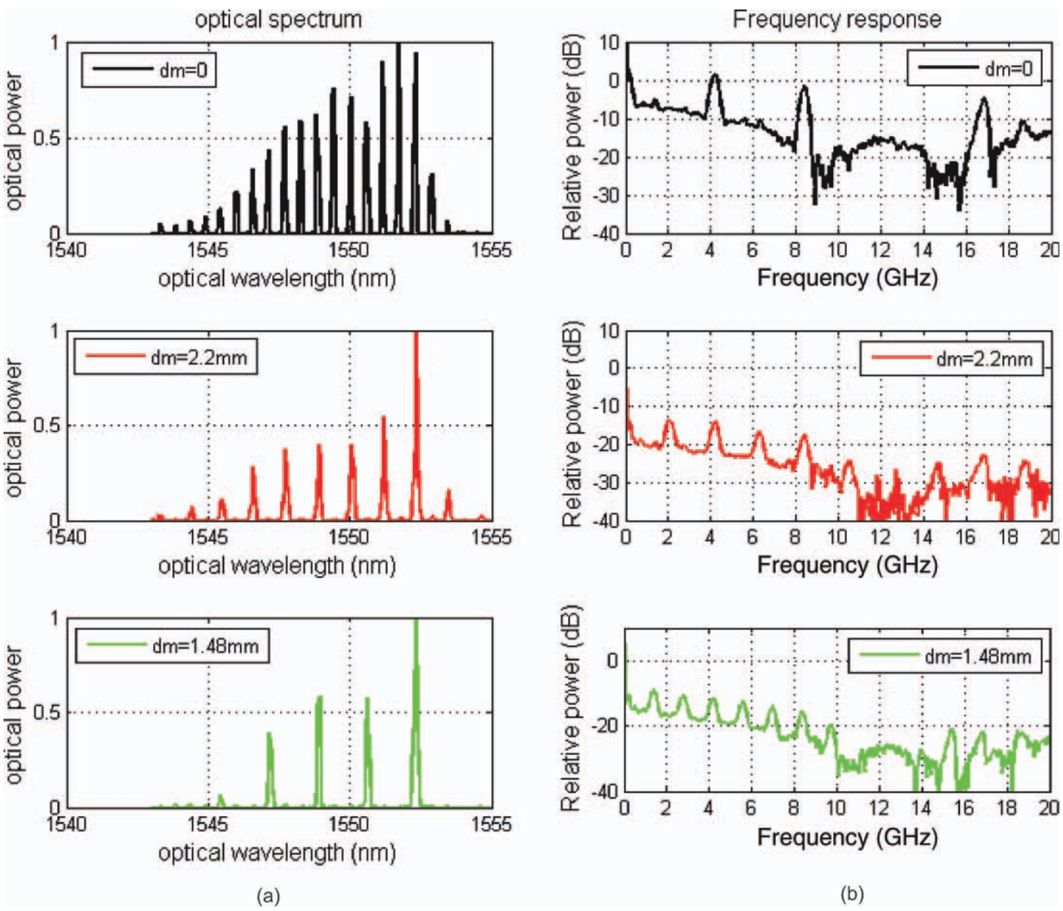

Figure 5 Experimental optical filtering and the corresponding frequency responses: upper graphs, no optical filtering; middle graphs, optical filtering of 2.2 mm; lower graphs, optical filtering of 1.48 mm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

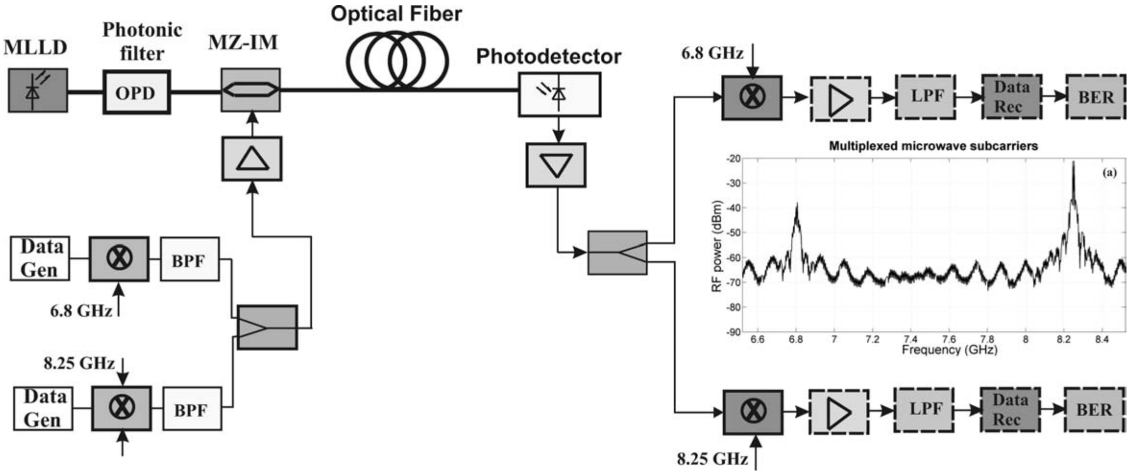

Figure 6 Experimental setup for transmitting multiplexed data-modulated microwave subcarriers in band-pass windows. Inset (a), multiplexed data-modulated microwave subcarriers at 6.8 and 8.25 GHz

centered at 2.1•n GHz. The lower graph in Figure 5(b) corresponds to the frequency response for an OPD of 1.48 mm. In this last case, the frequency response shows microwave bands centered at 1.05•n GHz. Such responses are in good agreement to the theoretical model.

5. EXPERIMENTAL MULTIPLEXED TRANSMISSION USING MICROWAVE SUBCARRIERS IN ADJACENT BAND-PASS WINDOWS

To show potential applications of the multilongitudinal source-dispersive channel scheme in the field of radio over fiber telecommunications, work has been conducted to show the transmission of multiplexed digital data-modulated microwave subcarriers, which were allocated at adjacent transmission windows around 7 and 8 GHz. Such bands were generated when the laser spectrum was filtered by an OPD of 1.48 mm [lower graph in Fig. 5(b)]. The experimental multiplexing transmission scheme is depicted in Figure 6. This scheme has been implemented using the multimode laser, a photonic filter introducing an OPD of 1.48 mm, a 20 GHz Mach-Zehnder electro-optic modulator, 25.2 km optical fiber channel, a 25 GHz photoreceiver, and home-designed microwave electronics (amplifiers, oscillators, mixers, etc). To test the multiplexed optical transmission, data streams of 34 Mbps, 2^{23-1} NRZ and RZ formats were used to modulate the 6.8 and 8.25 GHz microwave subcarriers. The modulated subcarriers were transmitted through the optical channel. At the receiver, the multiplexed microwave subcarriers were recuperated at the output of a low-noise amplifier stage. The

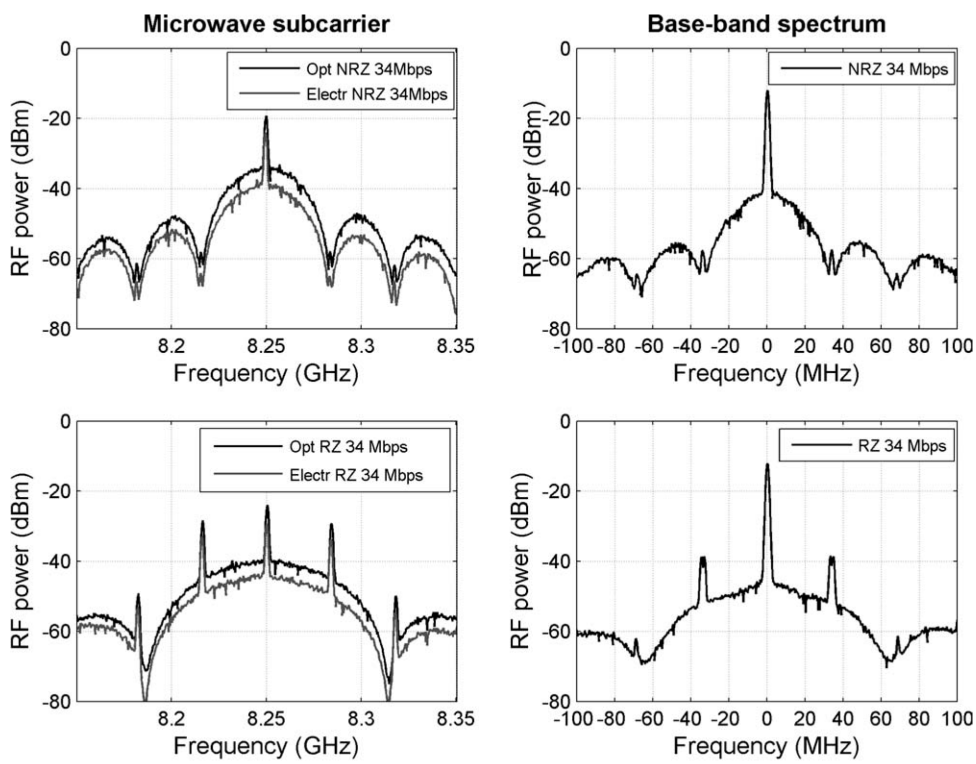

Figure 7 34 Mbps data-modulated subcarrier at 8.25 GHz: a) NRZ and RZ data formats; b) NRZ and RZ data spectrum after synchronous homodyne detection

received signals are naturally filtered by the transmission scheme and no electronic filters were used. Inset (a) in Figure 6, illustrates the multiplexed 6.8 and 8.25 GHz subcarriers. The system filtering effect is observed as the modulated spectra are confined around the center microwave frequencies. The laser noise level is at least −20 dB below the 6.8 GHz subcarrier level. As the 8.25 GHz subcarrier is the strongest signal, it has been chosen for demodulation to base-band by homodyne mixing, Figure 7. The graphs show the main lobes of the data signals, which can be recuperated by further signal processing. The optical link introduced an attenuation equivalent to 30 dB. The received optical signal was amplified and compared to the electrical microwave subcarrier after this one was attenuated by 30 dB. This comparison is illustrated in Figure 7(a), where both electrical and optical signals show the same spectral distribution. To recuperate the base-band digital data, the 8.25 GHz subcarrier was detected by synchronous homodyne mixing. In this stage, the received 8.25 GHz data-modulated subcarrier was mixed with an 8.25 GHz signal from a local oscillator. The resulting signal is the 34 Mbps base-band data stream, as depicted in Figure 7(b). The base-band signal was not further processed as this aspect was beyond the scope of this article. Work is in progress for integrating a complete data receiver [by adding the dashed line blocks in Fig. 7(b)], to evaluate the system performance, including parameters such as SNR, the BER, the dispersion power penalty, and so forth.

6. CONCLUSIONS

In the work, we have described the reconfiguration of the band pass transmission windows in the frequency response of an optical transmission system using a multilongitudinal laser and a dispersive optical channel. The introduction of optical delays can filter the optical spectrum in a way to increase the optical FSR. The optical delays must be matched to the spectrum characteristics to achieve the filtering effect. The number of band-pass windows on an experimental setup has been increased, as has been demonstrated in this work, when using OPDs of 2.2 and 1.48 mm.

The introduced OPD's have allowed a periodic filtering, eliminating alternate longitudinal modes. Such an effect introduced new band-pass windows in the resulting electrical microwave response of the studied scheme. The multiple band pass transmission windows, as described in this article, can be used for microwave filtering or multiplexing information on radio over fiber telecommunications schemes. Such capability has been successfully demonstrated by the simultaneous transmission of digital signals using microwave carriers located in two adjacent transmission windows. The proposed scheme would be able to transmit several information signals using the low-pass frequency band and either digital or analog modulated microwave carriers, using the band-pass windows.

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IMPROVED MODEL OF PSEUDOPOTENTIALS FOR ARRAY ELEMENTS

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ABSTRACT: *A recent article has proposed a simplified model, based on the quantum-mechanical concept of the pseudopotential, for certain types of array elements, particularly for short linear dipoles. A*