Automatic tunable and reconfigurable fiber-optic microwave filters based on a broadband optical source sliced by uniform fiber Bragg gratings

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Abstract: We demonstrate an automatic tunable transversal notch filter based on uniform fiber Bragg gratings and a broadband optical source. High tunability can be performed by stretching the fiber with the gratings written in series. Also, high sidelobe supression can be achieved by introducing tunable attenuators in a parallel configuration of the gratings.

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1. Introduction

During the last few years, microwave photonics has attracted the interest of many research groups. Different optical devices have been proposed for optical transporting and processing of microwave band signals, showing low loss or large bandwidth, reduced electromagnetic interference, among other typical advantages in optical systems. In many radio frequency systems, tapped delay line optical filters are needed for optical pulse train synthesis [1] or for filtering undesired noise and spurious signals [2]. Our work is focused on fiber optic transversal filters in which the RF signal is carried by the intensity modulated optical signal. These devices have many applications for RF signal filtering (i.e. Radar signal processing) or microwave and millimetre waveform generation, among others, and therefore require a tuning range around several tens of GHz, and an optimal main-to-sidelobe supression ratio of 30 dB.

In this context, there has been considerable work carried out on different approaches for transversal filtering [2-10]. The simplest alternative is based on single or multiple tunable laser sources [2-4] and chirped fiber gratings as dispersive elements. They show a large degree of flexibility, since optimum sidelobe supression (25 dB) has been achieved [3] apart from the RF tunability [4] in the 1-6 MHz range, but a large number of taps is limited by economical reasons. Fiber Bragg grating arrays and a tunable laser are also used to implement more sophisticated and expensive tunable filters showing 30 dB out-of-band rejection [5]. However, the use of optical broadband sources together with different spectral slicing techniques has been also proposed [6-8] as the cheapest alternative, but offering serious limitations of the filter performance and tunability. Examples of these use slicing elements, such as a filter Fabry-Perot [6], in which the Free Spectral Range (FSR) and intensity taps are fixed, or Arrayed Waveguide Gratings [7] in which tunability is not continuous and limited to 3 GHz. Fiber Bragg gratings (FBG) [8] also have been proposed as filtering elements in a two-tap filter, and they show a certain degree of tunability by stretching the FBG in a mechanical stage [0.6-1.6 GHz]. Finally, other recent approaches rely on polarization synthesis in high birefringence fiber Bragg gratings [9] or use tunable dispersion elements while optical taps are fixed [10], and have been demonstrated as promising tunable transversal filters.

In this paper, we demonstrate a new reconfigurable, tunable multi-tap transversal filter based on Fiber Bragg Gratings, which overcomes many of the limitations shown in previous work. As far as we know, we demonstrate a high performance and continuously tunable RF-filter with larger FSR tuning range and a simpler tuning scheme than in previously reported devices. Furthermore, it is a low cost tunable device whose performance can be easily improved by windowing the intensities of the optical taps.

2. Tunable Filter Description

The filter is based on a broadband optical source, i.e. a super-electroluminescent diode, SLED, and uniform fiber Bragg gratings as filtering elements. The output light of the source is driven to the FBG through an optical circulator, and the reflected signal will be driven through the same component to the rest of the system. The uniform FBGs are 5 cm-long and are written on photosensitive fiber in a series configuration, as shown in Fig. 1, and they will be stretched to tune the reflection bandwidth, initially centered at λ_{init}. When a fiber elongation, ΔL, is applied over a fiber length L_N, the original central wavelength of the grating N, λ_{init_N}, shifts by the following amount:

$$\Delta\lambda_N = \lambda_{init_N}\left(1 - p_e\right)\Delta L / L_N \qquad (1)$$

where p_e is the photoelastic coefficient of the optical fiber. Since the central optical frequency, ω_N, of different gratings must be equidistant [3], $\Delta\omega_N$, to implement the filter, and provided $\Delta\omega_N/\omega_N \ll 1$, the following condition must be satisfied:

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$$\Delta\lambda_N \propto N \cdot \Delta L \tag{2}$$

Therefore, each grating will be stretched over a different fiber length:

$$L_N = L/N\,, \tag{3}$$

so the total device length will be determined by the number of optical taps.

In such a device, a simple fiber stretching will tune the gratings differently to maintain their Bragg wavelengths spectrally equispaced. Figure 1 shows four uniform gratings on the mechanical stage, one of them is not glued on it, but the others are glued over a fiber length given by (3): N=0, not stretched, L_1=21, L_2=10.5 cm and L_3=7 cm. The reflected signal from the gratings can be monitorised by an optical spectrum analyzer, OSA, by using a 90-10 optical coupler, and the optical signal is amplitude modulated in an external electrooptic modulator, which RF-signal of frequency f is generated by a lightwave component analyzer, LCA. In our setup, an Erbium Doped Fiber Amplifier is used to compensate losses. A fiber length of 23 km will be the dispersive element in the filter, and finally, the transfer function of the filter is measured in the LCA. The inset of Fig. 1 shows the signal originally reflected by each one of the gratings, λ_{init_N} (N=0,1,2 and 3) centered at 1544.69, 1545.19, 1545.69, 1546.19 nm, respectively. In this case, Bragg gratings are identical and their initial response, λ_{init_N}, has been tuned by tension before gluing the grating on the mechanical stage.

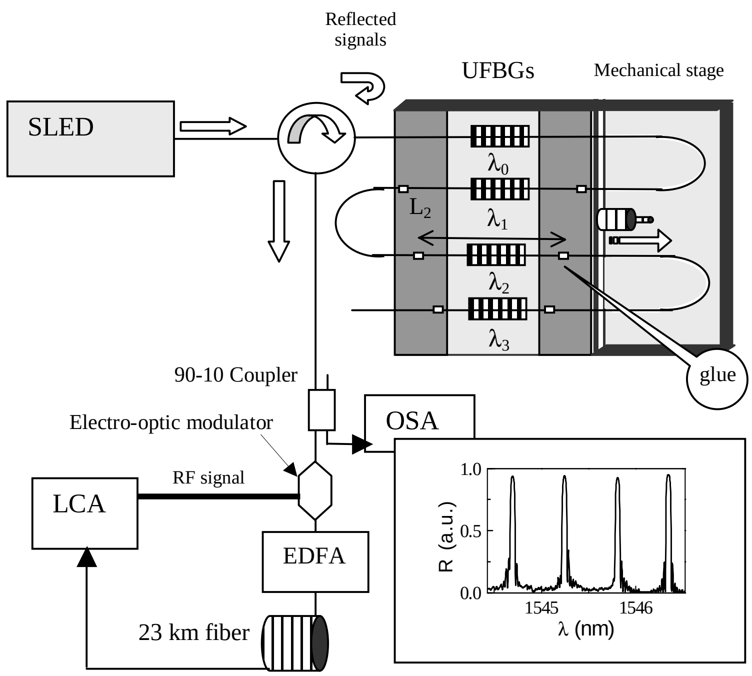

Fig. 1. Setup of the flexible uniform FBG-based RF filter. Inset: Reflectivity of the uniform gratings.

Figure 2 shows the wavelength tunability of all four optical taps corresponding to reflected signals by the gratings when different elongations are applied. The lowest wavelength is kept constant (the grating is not stretched, so $\lambda_0 = \lambda_{init_0}$) and the others show a linear behaviour, in such a way all of them are equidistant for different elongations. In this setup, the filter transfer funtion is given by the following expression [3]:

$$\left|H_{RF}(\Omega)\right| = \Re\left|\sum_{N=0}^{3} A_N \left[\int_{-\infty}^{+\infty} R_N(\omega) e^{j\beta\Omega\omega} d\omega\right] e^{-j\Omega\tau_N}\right| \tag{4}$$

where $\Re$ is the photodiode responsivity, A_N is the apodization factor or reduction of the reflected power of grating N, R_N is the reflectivity of the grating N, β is the linear fiber dispersion $(d\tau/d\omega)$ and $\Omega=2\pi f$ is the RF modulation angular frequency. The time delay value corresponding to signal reflected by each grating is $\tau_N = D \cdot \Delta\lambda \cdot L_F \cdot N$, where D is the fiber dispersion (17 ps/nm·km), L_F is the fiber length (23 km) and Δλ(nm) is the separation wavelength respect to λ_{init_0} .

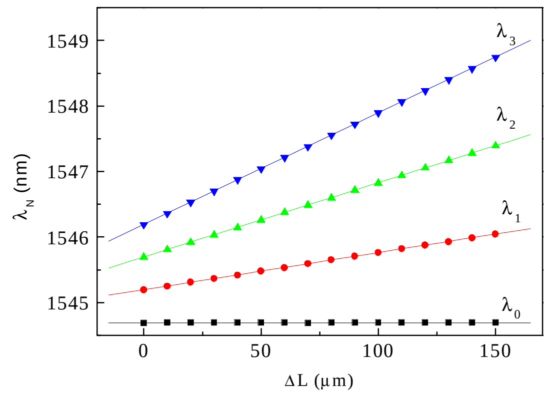

Fig. 2. Spectral position of the reflectivity peaks (filter taps) when the fiber is stretched.

Figure 3 shows the measured RF-transfer function of two filters corresponding to elongations of 123.0 (filter 1) and 25.7 μm (filter 2), with free spectral ranges, FSR, of 2.19 and 4.05 GHz, respectively, together with the theoretical calculation. The optical taps implementing these filters are spectrally spaced by 1.20 and 0.65 nm, respectively. Measurements are shown to agree perfectly with the simulation, with main to sidelobe ratio, MSLR, of 11.3 dB, and the main lobe shows a 3 dB bandwidth of 0.51 and 0.96 GHz, respectively.

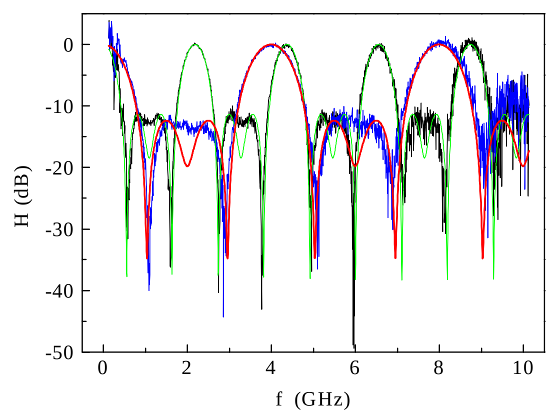

Fig. 3. Tunability of the RF-filters. Experimental (black: filter 1, blue: filter 2) and calculated (green: filter1, red: filter 2) filter response versus RF signal frequency with different spectral spacing between taps.

The system shows a broad tuning range, which has been plotted in Fig. 4. The free spectral range of a 4-taps RF filter has been measured (circles), and triangles represent the obtained results in a 3-taps filter (squares). Tuning is linear on the inverse of the wavelength spacing, i.e. the elongation, and perfectly agrees with the theoretical prediction (solid line). The FSR tuning range is shown to be 1-6 GHz, which is smaller of the real tuning range of these systems, as it will be discussed in section IV. However, in this system, the sidelobe supression level cannot be improved. At this stage, if improved performance of the filters is desired, we propose an alternative configuration, with the same basis as the one above.

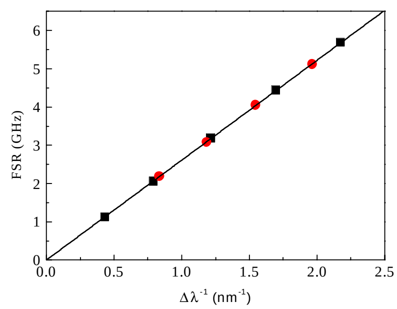

Fig. 4. Free spectral range of the RF filters dependence on the reciprocal of the wavelength spacing between taps. Theoretical calculation (solid line) and experimental results (●, 4 taps-based filter; ■, 3 taps-based filter).

3. Sidelobe Supressed Filters

We propose a similar configuration for a 4-tap filter where the gratings are written in a parallel configuration to achieve large sidelobe supression by weighting the taps. Figure 5 shows the new configuration of the gratings, which will show large flexibility in the implementation of the filters with the only drawback of larger optical losses, which will be compensated by the optical amplifier. The gratings are written in different arms of a 4x4 optical coupler and will be glued onto the mechanical stage over different fiber lengths, as explained above. As known from filter theory [3], the shape of the transfer function of a discrete time transversal filter can be changed or reconfigured by changing the optical power of the different taps according to an apodisation function. Therefore, a decrease in the secondary sidelobes of the filter can be achieved. The optical signals corresponding to the side taps (in our case, N=0 and N=3) will go through a 2 inputs variable attenuator, which will be varied according to the desired degree of MSLR of the RF-filter.

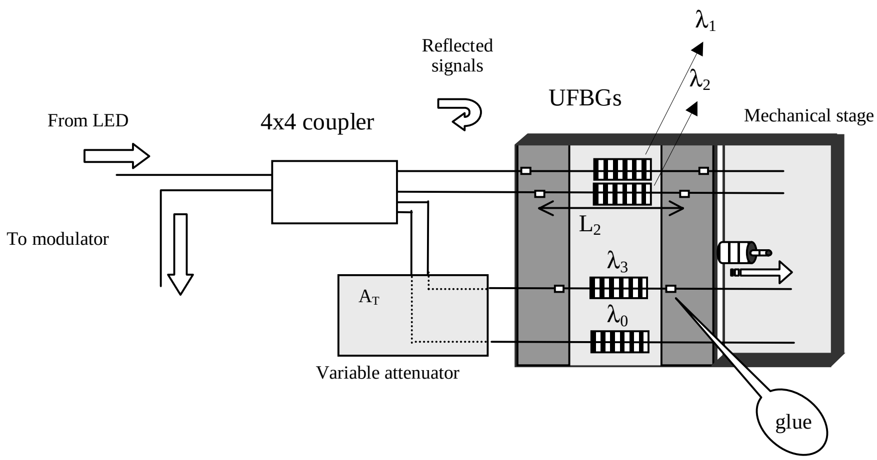

Fig. 5. System configuration for reconfigurable sidelobe supression.

Figure 6 shows the measured main to sidelobe ratios of implemented RF-filters by introducing different attenuation values to the optical signal taps (see AN in equation (4)), together with the theoretical curve. As an example, the intensity of the four taps of two filters is shown in two different insets, exhibiting different apodisation profiles. The uniform intensity pattern leads us to the theoretical (and measured) limitation of 11.3 dB and sidelobe reduction has been demonstrated in these filters up to 25 dB. However, the MSLR can be improved by using more accurate and electronically controlled tunable attenuators.

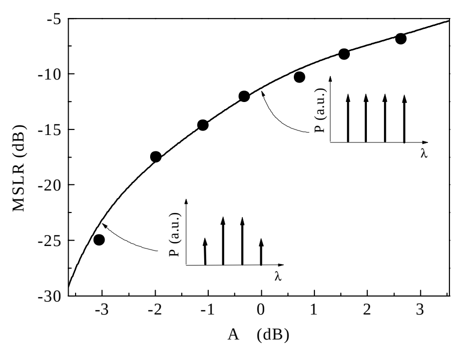

Fig. 6. Calibration curve of sidelobe supression versus attenuation tuning parameter. Insets: intensity of the taps in different filters.

Figure 7 shows the transfer function of the transversal filters with different degree of apodisation (measured MSLR of 6.9 –where optical taps are not balanced-, 12.1 and 17.5 dB). Measurements and theoretical calculations are shown to fit well. The RF-bandwidth of the main lobe of these filters are 0.55, 0.66 and 0.70 GHz, respectively.

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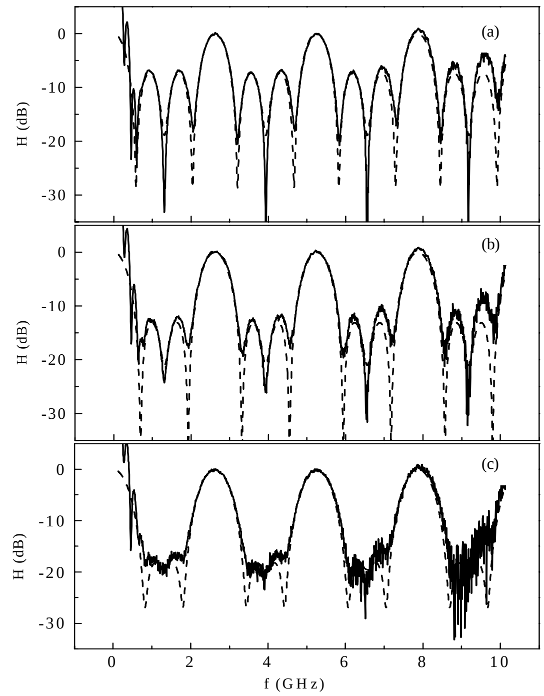

Fig. 7. Reconfigurable sidelobe supression of the RF-filters. Experimental (solid line) and calculated (dashed line) filters response with different extinctio ratios: (a) 6.9 dB, (b) 12.1 dB and (c) 17.5 dB.

4. Discussion and Conclusions

The filters presented in the paper are demonstrated to have a high degree of flexibility and reconfigurability. However, a detailed study requires an estimation of the limitations of the tunability and other performance characteristics of these filters.

Maximum spectral spacing between optical carriers, $\Delta\omega_{max}$, provided the gratings are identical, will be determined by the number N of Bragg gratings and the maximum wavelength shift will be given by the fiber breakdown limit:

$$\delta\omega_{max} = \Delta\omega_{max}/N \tag{5}$$

The RF-frequency of the first notch in the filter transfer function is given by the fiber dispersion:

$$1/f_{notch} = \beta\delta_{max} = \beta\Delta\omega_{max}/N \tag{6}$$

Minimum separation between optical taps will be given by their bandwidth since no overlapping between them must be provided. Therefore, the tuning range is given by the following limits:

$$1/f_{notch} \in \left[\beta\delta\omega_{3d\mathbf{B}}, \beta\Delta\omega_{max}/N\right] \tag{7}$$

As an example, a filter based on 10 uniform fiber gratings with a 3 dB bandwidth of 0.05 nm, a total tuning of 10 nm, and taking 50 km of standard fiber as dispersive element $\left(\beta/L = 21.6\, ps^2/km\right)$ would have the FSR frequency tuning range of [1.18-23.5] GHz. These values show the large potential of these filters when external parameters are properly chosen.

In conclusion, we have demonstrated new low cost and tunable RF transversal filters based on a broadband source and uniform fiber Bragg gratings with tunability in the 1-6 GHz range, although the tuning range of the device can be significantly enhanced by chosing the design parameters, as explained above. Also, these filters allow an optimization of the performance by means of reducing the sidelobe level in a similar configuration where the uniform gratings are placed in the coupler arms, with the only drawback being larger losses that could be compensated by an optical amplifier. Sidelobe level reduction up to 25 dB has been demonstrated. Examples of specific applications exploiting our system advantages are radar signal processing, noise filtering in RF systems or label swapping in all optical networks. Finally, all the measurements of RF filters presented in this paper are shown to be in perfect agreement with theoretical predictions.

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