Photonic Microwave Filter Using a Broadband Source Sliced by a Birefringent Optical Fiber-Based Interferometer

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Abstract — **An experimental and theoretical demonstration of a non-periodic photonic microwave filter is reported. The finite impulse response (FIR) is realized in the optical domain by slicing an optical broadband source with an interferometric scheme based on a birefringent optical fiber. This simple optical operator permits an easy adjustment of the center frequency of the filter with the length of this fiber and opens the potentiality of frequency tuneability.**

I. Introduction

The possibility to achieve a microwave response by modulating optical carriers with radio frequency (RF) information has led to a new attractive field: microwave photonics. This takes advantage of wide pass band operation, low loss propagation and the immunity of electromagnetic disturbances of optical structures.

The RF signal, modulating the intensity of the optical carriers, can be delayed by an optical fiber and recovered after propagation by high speed photodiode. Thus, finite impulse responses and transversal-like filters can easily be achieved. The optimal such filter has to be non periodic, frequency tunable and reconfigurable band pass at microwave frequencies. Moreover, a high rejection ratio is required. The tuneability of the filter could be achieved by a basic delay change. Control of the weights of the optical carriers allows the reconfiguration of the filter response.

Periodic photonic filters have already been realized using tunable laser source(s) and fiber with multiple (chirped) Bragg gratings [1], [2]. The advantages of these filters are their tuneability and reconfiguration capabilities. But the discrete sampling time of the finite impulse response obtained after the fiber Bragg gratings has to be larger than the laser coherence time since incoherent summing of the modulated carriers has to be realized at the detection line.

Thus, the sampling frequency, inversely proportional to the discrete sampling time, together with the free spectrum range (FSR) are up limited. These limitations can be overcome by the use of a tunable laser source array, but it could be an expensive alternative for a large number of taps (optical sources) [3].

Another solution is to realize a spectral slicing of a broadband optical incoherent source using an optical filters and also avoiding the requirement of multiple wavelength sources. In this paper, we present an original and low cost, simple and stable slicing filter based on optical interference between the two degenerated polarization modes using few meters of a highly birefringent fiber.

A description of the slicing optical filter operation is provided in Section II. The theoretical formulation leading to the evaluation of the RF filter transfer function is provided in Section III. In Section IV, experimental results are shown together with the description of the non-periodic filter and confirm our theoretical background and the potentiality of such systems to be tunable.

II. General Principle of the Slicing Filter

The general layout of the microwave filter based on slicing optical spectrum is presented in Fig. 1. It is composed of a broadband optical source sampled by an optical filter, such as Fabry-Perot filter [4], fiber Bragg gratings filter [5] or a Michelson Interferometer.

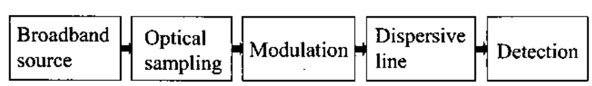

Fig. 1 : General layout of a slicing filter

Then, the microwave signal is applied to the RF input of the electro-optical modulator to modulate the intensity of the lightwave coming out from the optical filter. The equispaced selected wavelengths, all modulated by the same RF signal, will fed a dispersive optical fiber and be submitted to different speeds and also different delays by means of the fiber chromatic dispersion. These delays are separated by the same incremental delay-time τ between two corresponding adjacent optical carriers. After dispersion, a photodiode sums the currents generated by each time-delayed spectral elementary component.

The microwave filter of transfer function $H(f) = FT[h(t)]$ is achieved by the realization of the impulse response h(t) using the dispersion properties of the optical fiber.

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Thus, the different wavelengths spectrally equispaced by $\delta\lambda$ coming out from a multi-chromatic source will be separated by the same delay-time δT given by:

$$\delta T = D.L.\delta\lambda \qquad (1)$$

where D(ps/km/nm) and L(m) are the dispersion and the length of the dispersive fiber, $\delta\lambda$(nm) and δT(ps) are the spectral and time-domain spacing respectively.

Thus, the impulse response shape is imposed by the spectrum of the optical source $g(\lambda)$:

$$h(t - T_0) = g((\lambda - \lambda_0)/D.L) \qquad (2)$$

where λ_0 is a reference wavelength arbitrary chosen within the optical spectrum and T_0 the time needed by this wavelength to travel along the dispersive fiber. The characteristic of the microwave filter is thus synthesized by filtering a continuous optical spectrum so that the envelop of the desired impulse response (a function of time) corresponds to the spectral density shape (a function of wavelength).

III. THEORETICAL FORMULATION

A. General model

The determination of the transfer function can be performed referring to the filter scheme in Fig. 2. We demonstrate here the frequency response of the transversal filter given in [5] when the optical filter is a Fabry-Perot filter. The optical blocks of Fig. 1 can be identified in Fig. 2 in this case. The broadband optical source used is the Amplified Spontaneous Emission (ASE) generated by an erbium-doped fiber amplifier and approximated by a gaussian function noted $g(\lambda)$. The transmittance $T_{OF}(\lambda)$ (i.e. the optical response) of the optical filter is derived by considering an elementary sampling pattern noted $s(\lambda)$ repeated with a spectral period $\delta\lambda$. The transmittance can be written as:

$$T_{OF}(\lambda) = s(\lambda) \underset{(\lambda)}{*} \sum_{k=-\infty}^{+\infty} \delta(\lambda - k.\delta\lambda) \qquad (3)$$

The symbol $\underset{(\lambda)}{*}$ represents the convolution product in the spectral domain.

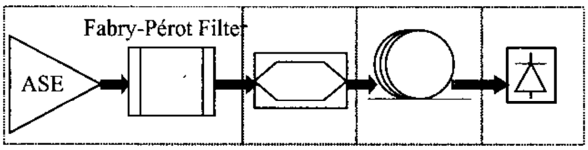

Fig. 2 : Layout of the filter given in [5]

The sliced optical spectrum $g_s(\lambda)$ at the output of the optical filter is obtained by multiplying the signal of the source by the transmittance of the filter. The bandwidth of the optical source $\Delta\lambda$ limits the number of carriers to 2N+1. Sampled spectrum is then equal to:

$$g_s(\lambda) = g(\lambda) \left[\sum_{k=-N}^{N} \delta(\lambda - \lambda_0 - k.\delta\lambda) \underset{(\lambda)}{*} s(\lambda) \right] \qquad (4)$$

$$g_s(\lambda) = g(\lambda). \sum_{k=-N}^{N} s(\lambda - \lambda_0 - k.\delta\lambda) \qquad (5)$$

The microwave signal x(t) is applied to the RF input of an electro-optical modulator for intensity modulation of the spectrum provided at the output of the optical filter. The power of each wavelength pattern is so modulated in the time-domain by the microwave signal. The signal $\tilde{x}(t,\lambda)$ at the output of the modulator is then given by:

$$\tilde{x}(t,\lambda) = g(\lambda).x(t) \qquad (6)$$

At this step, the sampling pattern $s(\lambda)$ can be derived from the Dirac sampling. We will show further which role is played by a non ideal sampling pattern on the final global response. Under this assumption, the modulated signal for a given time τ can be written as:

$$\tilde{x}(\tau,\lambda) = x(\tau). \sum_{k=-N}^{N} a_k.\delta(\lambda - \lambda_0 - k.\delta\lambda) \qquad (7)$$

where a_k represents the output power from the k^{th} optical carrier in the spectrum:

$$a_k = g(\lambda_0 + k.\delta\lambda) \qquad (8)$$

The RF modulated spectrum is then fed to a dispersive fiber providing a linear delay characteristic. Assuming that the dispersion of the fiber is constant, two adjacent optical carriers will be delayed from each other by the incremental differential delay δT in reference to equation (1). If λ_k represent the k^{th} carrier wavelength, the delay due to the propagation through the optic fiber is given by:

$$T(\lambda_k) = T_0 + k.\delta T \qquad (9)$$

Thus, the signal $y(\tau,t)$ at the output of the dispersive fiber corresponding to a time-domain sample of the signal injected at the input of the fiber at τ is given by:

$$y(\tau,t) = x(\tau). \sum_{k=-N}^{N} a_k.\delta(t - \tau - T_0 - k.\delta T) \qquad (10)$$

At the output of the fiber y(t) results from the sum of all the contributions of each sample signal injected into the fiber at different times τ.

$$y(t)=\int_{-\infty}^{+\infty}x(\tau).\sum_{k=-N}^{N}a_k.\delta(t-\tau-T_0-k\delta T)d\tau \quad (11)$$

$$y(t)=\sum_{k=-N}^{N}\left[a_k.x(t-T_0-k.\delta T).\int_{-\infty}^{+\infty}\delta(t-\tau-T_0-k.\delta T)d\tau\right] \quad (12)$$

This calculation corresponds in fact to a time-domain convolution between the input signal and the impulse response of the optical system. Moreover, the transversal-like impulse response h(t) is obtained when x(t) = δ(t), then:

$$h(t)=\delta(t-T_0)\underset{(t)}{*}\sum_{k=-N}^{N}a_k.\delta(t-k.\delta T) \quad (13)$$

Now, to take into account the case of the gaussian sampling pattern s(λ) with spectral $\Delta\lambda_s$, bandwidth, each pulse will be time-convoluted with a corresponding gaussian pulse s(t) of short duration $\Delta T_s = D.L.\Delta\lambda_s$. The impulse response h(t) becomes:

$$h(t)=\delta(t-T_0)\underset{(t)}{*}s(t)\underset{(t)}{*}\sum_{k=-N}^{N}a_k.\delta(t-k.\delta T) \quad (14)$$

The output signal from the dispersive fiber is fed to a photodiode with a receiver sensitivity R. The RF transfer function is then given by:

$$H(f)=K.S(f).\sum_{k=-N}^{N}a_k.e^{-j2\pi.f.k.\delta T} \quad (15)$$

where K is a complex constant proportional to the receiver sensitivity of the photodiode and S(f) = TF [s(t)]. The function S(f) has a wide frequency support thus leading to an attenuation of the frequency magnitude repeating response patterns. In the general case, H(f) is constituted of a spectral pattern, periodically repeated at frequencies multiple of f_0, such as:

$$f_0=\frac{1}{\delta T}=\frac{1}{D.L.\delta\lambda} \quad (16)$$

At this point it can be noted that tuneability can be achieved by tuning the spectral sampling value δλ.

B. Optical implementation

In our case, the general layout of our slicing spectrum filter is presented in Fig. 3. The optical elements of the RF filter are the same than those described in Section III. The optical sampling process is now realized by means of an optical modulation with a trigonometric function using an interferometric operation. As shown further, with this method, a single band pass pattern is obtained at the central frequency f_0 (see (16)).

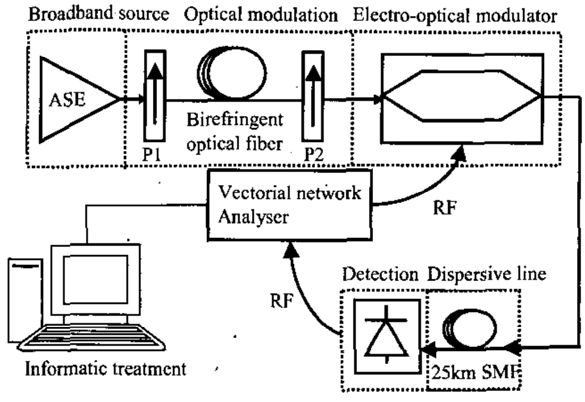

Fig. 3 : Experimental bench

The spectral modulation is realized by an interferometric scheme including two polarizers and a birefringent fiber (Fig. 4). Two different indices exist along the two polarization axes of the birefringent fiber, leading to two propagation speeds.

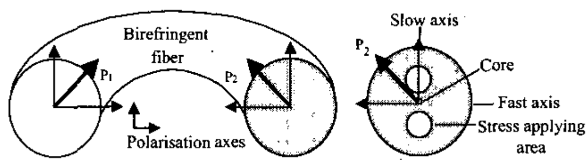

Fig. 4 : Optical interferometer using birefringent fiber - fiber structure with slow and fast birefringent axes

The light from the source is injected into the polarizer P_1 oriented 45° from the polarization axis of the fiber structure. Therefore the two orthogonal polarization modes equally excited will experience different optical paths after traveling through a length of the birefringent fiber. At the output of this fiber, the polarizer P_2 (Fig. 4) has the same direction than P_1 and sums the two orthogonal polarization modes to obtain the slicing effect on the output spectrum thanks to the phase difference between the two modes (Fig. 5b). This technique provides an easy adjustment of the step of modulation (and thus the center frequency of the filter) by optimization of the length of the birefringent fiber. This approach only needs a few meters of fiber and is optically stable (no optical alignment needed).

IV. Experimental Results

The Fig. 5a shows the spectral response of the optical ASE source. As noted, spectrum is mainly centered at λ_0=1535.5nm. Therefore, gaussian shape of the optical source (and also of the impulse response) can be assumed. The obtained sliced spectrum $g_s(\lambda)$ (Fig. 5b) corresponds to the product of the ASE spectrum with a cosine function:

$$g_s(\lambda) = g(\lambda).(1+V.\cos(\phi)) \quad (17)$$

with $$\phi = \frac{2\pi}{\lambda} L_B.(n_x^{eff} - n_y^{eff}) \quad (18)$$

where ϕ is the phase difference between the two orthogonal polarization modes at the output of the birefringent fiber. L_B is the birefringent fiber length, n_x^{eff} and n_y^{eff} are the effective indices following the two principal axes. V is called the factor of visibility close to the unity.

From the previous equation, the spectral step of modulation can be calculated and can be considered as constant (Fig. 5b) in the spectral band of the source centered at λ_0:

$$\delta\lambda = \frac{\lambda_0^2}{L_B.(n_x^{eff} - n_y^{eff})} \quad (19)$$

The birefringent fiber used has a effective indices difference equal to B = 4.65.10^{-4}, and is 8.5m long. The theoretical spectral step is equal to $\delta\lambda$ = 0.596nm. The dispersion of the dispersive fiber is equal to 16ps/(km.nm) (taken at λ_0) over the whole source spectrum. From equation (16) we can also calculate the theoretical center frequency of the filter f_0 = 4.19GHz.

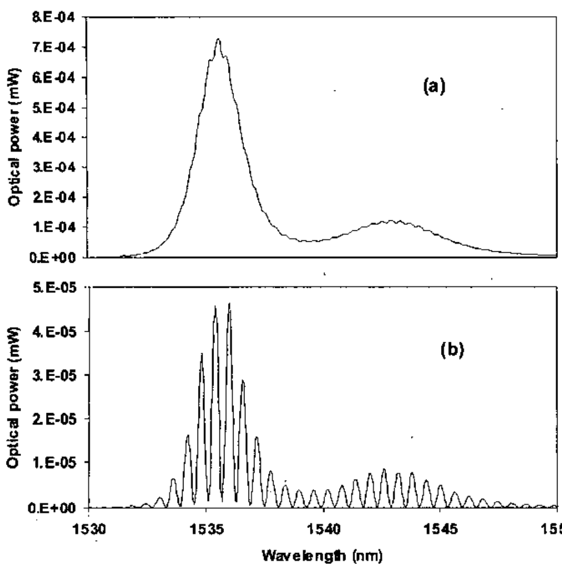

Fig. 5 : Optical ASE source (a) and sliced spectrum at the output of the birefringent fiber (b)

Fig. 6 shows the frequency response obtained using a vector analyzer. The thick curve corresponds to the experimental results and the thin one is derived from the programming of equation (15) and using the numerical data of Fig. 5b.

The response of the filter is centered around 4.12GHz in accordance to the theory. It can be noted that the filter has a gaussian-like shape imposed by the shape of the spectrum of light source (Fig. 5a). The filter presents a bandwidth of 2GHz and a relative attenuation of 30dB on the secondary lobes.

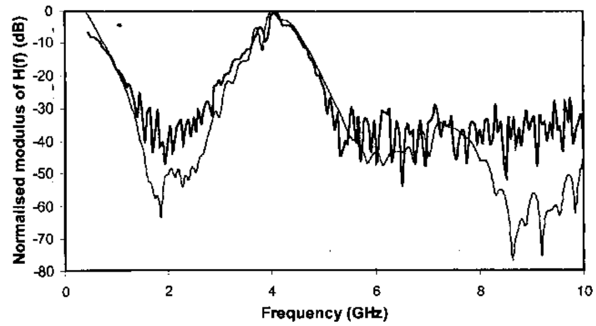

Fig. 6 : Theoretical and experimental responses of the transversal-like filter

V. Conclusion – Ongoing research

Using a birefringent fiber, we have proved the feasibility of a non-periodic transversal-like filter which center frequency is set by the adjustment either of the birefringent fiber length or the dispersive fiber length. Improvement of the performances of the RF filter can be easily obtained with a wider spectrum optical source. Moreover, the tuneability property can be carried out by a controlled variation of the spectral sampling step. This can be done by modifying the intrinsic or physical characteristics of the birefringent fiber by imposing stress or stretching.

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