Analysis and Performance of Photonic Microwave Filters Based on Multiple Optical Carriers

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Abstract. In this paper a Photonic microwave filters are photonics sub system design with aim of carrying equivalent tasks to those an supplementary advantage inherent to photonics such as low lass, high band width, immunity to electromagnetic inference (EMI), tunability, reconfigurability, reduced size and weight, and low and constant electrical loss. Many photonic microwave filter architectures have been proposed over the last years using a variety of fiber-optic devices. Some of them are based on using multiple optical carriers wavelength-division multiplexing (WDM)] and dispersive media to obtain a set of time-delayed samples of the RF input signal. In this paper, the statistical analysis of the performance of photonic microwave filter is based on multiple optical carriers (WDM) and a dispersive medium, with random errors in amplitude and wavelength spacing between optical carriers is presented.

Keywords: Microwave Photonics, Photonic Microwave filter, Transversal filter, Wavelength Division Multiplexing (WDM). Optical Source.

1 Introduction

The Use of photonic technology for microwave and millimeter-wave filtering is an interesting alternative to conventional electrical processing. Photonic microwave filters benefit from fiber-optic advantages such as high time-band width product operation, immunity to electromagnetic inference (EMI), reduced size and weight, and low and constant electrical loss. An enabling technology to obtain this objective is based on optical carrier radio over fibers system where signal processing is carried at a central office where signal carried from inexpensive remote antenna units (RAU). On other hand, microwave photonic filters can find application in specialized field such as radar and photonic beam steering of phased-arrayed antennas, where dynamic reconfiguration is an added value.[3-4]

Many photonic microwave filter architectures have been proposed over the last years using a variety of fiber-optic devices [1]-[8]. Some of them [5] are based on

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using multiple optical carriers i.e. wavelength-division multiplexing (WDM) and dispersive media to obtain a set of time-delayed samples of the RF input signal.

In this paper, the effect of these errors on the filter transfer function is performed. Simulations are performed assess the design and experimental results verify the validity of the expressions are provided.

2 Theory

The transfer function of an *N*-tap WDM photonic microwave filter for an optimum polarization adjustment and neglecting the carrier suppression effect (e.g.., using a single-sideband modulation [9]) is given by [6]

$$H_{RF}(f) = \Re \sum_{k=0}^{N-1} P_k (1+\Delta_k)\ e^{-j2\pi\ fDL[k\Delta\lambda+\varepsilon_k]} \tag{1}$$

where f is the electrical frequency $\Re$ is the photodiode responsivity, P_k is the optical power of source *k*, the amplitude error of carrier *k* is Δ_k *D* is the dispersion parameter, *L* is the dispersive fiber coil length, $\Delta\lambda$ is the nominal wavelength spacing, and ε_n is the wavelength spacing error.

The ensemble average of the squared transfer function (magnitude) of a filter can be obtained as

$$\overline{|H(f)|^2} = \overline{H(f)\cdot H^*(f)}$$

$$= \Re \left(\sum_{k=0}^{N-1} P_k (1+\Delta_k) e^{-j2\pi f DL[(k-n)\Delta)+e_k-e_n]} \right) \tag{2}$$

Assuming that amplitude and spacing errors have zero-mean Gaussian distribution equation (2) is expressed as

$$\overline{|H(f)|^2} = = \Re \sum_{k=0}^{N-1} \sum_{n=0}^{N-1} P_k P_n (1+\Delta_k)(1+\Delta_n) e^{-j2\pi \mathrm{f}\ DL[(k-n)\Delta\lambda+e_k-e_n]} \tag{3}$$

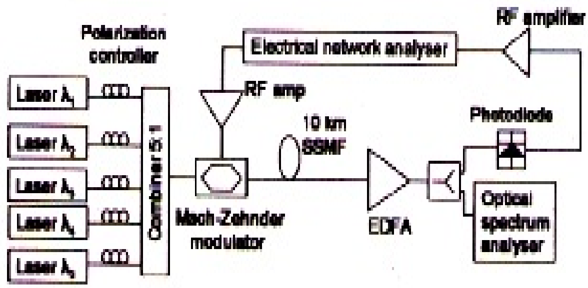

Fig. 1. Experimental setup for random error evolution using five optical source of different wavelength and an SSMF coil of 9 -10 Km as a dispersive element

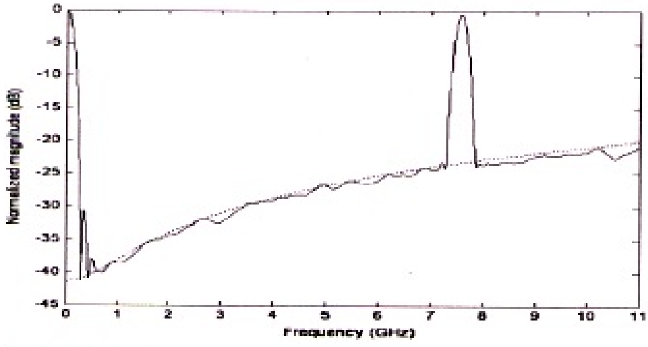

Fig. 2. Simulated average squared transfer function of 100 filters of 50 taps using a Hanning Window with amplitude and wavelength spacing errors of a standard deviation of 0.05(solid line)

Evaluating (3) for the terms with $k = n$ and $k \neq n$.

$$\overline{|H(f)|^2} = \Re^w \sum_{k=0}^{N-1} P_k^2 (1+\Delta_k)^2 \tag{4}$$

$$= \sum_{k=0}^{N-1} P_k^2 (1+\overline{\Delta}^2 + 2\overline{\Delta}), k = n \tag{5}$$

where it has been considered that the error sources are independent random processes and that every optical source has the same error statistics. Combining equation (4) and (5), the average of the squared transfer function of a filter yields

$$\overline{|H(f)|^2} = \Re^2 \cdot \left[\overline{(1+\Delta)^2} \sum_{k=0}^{N-1} P_k^2 + (1+\overline{\Delta}^2) \overline{e^{-j2\pi \mathrm{f}DL\varepsilon}} \right.$$
$$\left. \overline{.e^{j2\pi \mathrm{f}DL\varepsilon}} \left(\sum_{k=0}^{N-1} \sum_{\substack{n=0 \\ n\neq k}}^{N-1} P_k P_m \overline{e^{-j2\pi fDL(k-n)\Delta\lambda}} \right) \right] \tag{6}$$

The last term in parenthesis in equation (6) is the filter transfer function without errors, except for the term $k = n$. If this term is added and subtracted, the average squared transfer function of the filter is given by

$$\overline{|H(f)|^2} = \Re^2 \left(\left(\overline{1+\Delta} \right)^2 - (1+\overline{\Delta}^2) \overline{e^{-j2\pi fDL\varepsilon}} \cdot \overline{e^{j2\pi fDL\varepsilon}} \right) \sum_k P_k^2$$
$$+ \left(1+\overline{\Delta}^2 \overline{e^{-j2\pi fDL\varepsilon}} \cdot \overline{e^{j2\pi fDL\varepsilon}} \, |H_0(f)|^2 \right) \tag{7}$$

From (7), it can be seen that the average squared transfer function of a filter with errors is the superposition of the squared transfer function of the ideal filter (without errors) and an error term, which depends on frequency. If the transfer function is normalized in such a way that the transfer function without errors is unity at $f = 0$, the error term can be read as the side lobe level relative to the peak of the main lobe[7]. The average squared transfer function of the filter with errors at $f = 0$ is given by

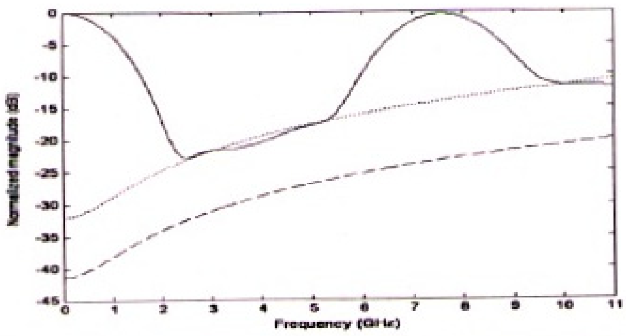

Fig. 3. Simulated average squared transfer function of 100 filters of five taps using a Hanning window with amplitude and wavelength spacing errors of a standard deviation of 0.05 (solid line). The dotted line corresponds with the estimation provided by (10) for a five tap filter and the dashed line corresponds with the residual sidelobe level for a 50-tap filter

$$\overline{|H(0)|^2} = \Re^2\left((1+\Delta)^2 - \left(1+\overline{\Delta}^2\right)\right)\sum_k P_k^2 + \Re^2\left(1+\overline{\Delta}^2\right)\left(\sum_k P_k\right)^2 \tag{8}$$

where the term $\left(\sum_k P_k\right)^2$ is usually larger than $\left(\sum_k P_k^2\right)$ and, therefore, the first term in (8) can be neglected. Thus, the average squared transfer function of the filter with errors at $f = 0$ is approximated by

$$\overline{|H(0)|^2} \approx \Re^2\left(1+\overline{\Delta}^2\right)\left(\sum_k P_k\right)^2 \tag{9}$$

Diving (7) by (9), the normalized average squared transfer function of the filter with errors can be expressed as where the first term is a residual sidelobe level due to random errors. This term is simplified if the error statistics are known.

Usually the system will be calibrated and, therefore, the mean of the amplitude and spacing errors will be zero $\left(\overline{\Delta} = 0, \overline{\varepsilon} = 0\right)$.

in this case.

$$\overline{\sigma^2} \approx \frac{\left(\left(1+\overline{\Delta^2}\right)e^{-j2\pi fDL\varepsilon} \cdot e^{-j2\pi fDL\varepsilon} - 1\right)}{\left(\sum_k P_k\right)^2}\sum_k P_k^2 \tag{10}$$

3 Simulation Results

Simulations from equation (1) is used to calculate filter squared transfer functions with random errors. By averaging these functions. It is then possible to compare these results with the residual side lobe level given by equation (7). Fig. 1 depicts the average squared transfer function (solid) of 100 filters with amplitude and wavelength spacing errors between carriers of a standard deviation of 0.04 and 0.05, respectively, for filters of 50 taps, using a nominal wavelength spacing of 0.9 nm and being the nominal amplitude of a Henning window. The dispersive medium is a coil of standard single-mode fiber (SSMF) of 9-10-km length and with D=16.4 ps/(nm.km).

Moreover, the residual side lobe level depends on the number of taps, the number of optical carriers, as can be seen from (8) Fig. 2 depicts the average transfer function of a filter equal to the one shown in Fig. 1 but using five taps.

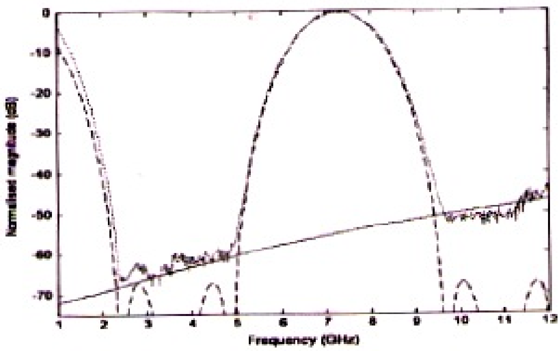

Fig. 4. Measured average squared transfer function (dashed line), transfer function with a hanning window without errors (dashed line),and residual side lobe level due to amplitude (std=0.02) and wavelength spacing (std=0.01) random error (solid)

4 Experimental Results

The analysis & verify the validity of the previous expressions and to demonstrate the effect of amplitude and spacing random errors on the transfer function of WDM photonic microwave filters, measurements have been carried out in the laboratory using the experimental setup shown in Fig. 1.A five-tap filter has been implemented using four distributed feedback (DFB) lasers and one external cavity laser (ECL) with a nominal wavelength spacing between carriers of 0.9 nm and using a Henning window [-6.05 -1.250 - 1.26-6.02] dB as nominal amplitude distribution. This window has a low side lobe level and, thus, the residual side lobe level is properly displayed. The dispersive medium used has been a coil of 10 km approx. of SSMF.

To study the performance of the transfer function with errors. 14 transfer functions have been measured under random amplitude and spacing errors of a standard deviation of 0.02 and 0.01 respectively. These values were measured using the optical spectrum analyzer (OSA) of the setup of Fig. 3, 4 shown the average squared transfer functions of the 14.5 measured squared transfer functions (dotted line), the ideal squared transfer function (without errors) using a five-tap Hanging window (dashed line), and the residual side lobe level solid line) obtained from (7-8) due to random errors in amplitude and wavelength spacing of a standard deviation of 0.02 and 0.01 respectively. From this figure, it can be seen that (7) provides a good estimation of the residual side lobe level from the standard deviation of amplitude and wavelength spacing between carriers errors.

5 Conclusion

The analysis of amplitude and wavelength spacing random errors in photonic microwave filters based on multiple optical carriers and a dispersive medium has been theoretically derived. These errors translate in a residual side lobe level of the filter response dependent of the statistics of the random errors. An expression for the residual side lobe level has been developed. Simulation and experimental results showing a good agreement with theory have been provided.

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