Optics Communications 283 (2010) 1320–1325

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Tunability of the multiple-bandpass response of cascaded single-source and continuous-sample microwave photonic filters

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ARTICLE INFO

Article history:
Received 16 July 2009
Received in revised form 26 November 2009
Accepted 26 November 2009

Keywords:
Microwave photonic filter
Optical signal processing
Broadband source
Radio-frequency photonics

ABSTRACT

We report a theoretical and experimental investigation on the structure and tuning capabilities of cascaded associations of microwave photonic filters composed of a single-source incoherent filter and a continuous-sample filter based on periodically-sliced broadband sources that undergo dispersion after being modulated. We derive the condition that guarantees both incoherent operation and cascading of the radio-frequency responses. This condition implies a lower bound for the ratio between resonance bandwidth (Δf) of the continuous-sample filter and the free spectral range (*FSR*) of the single-source filter, thus showing the possibility of cascading filters in two complementary regimes, $\Delta f/FSR < 1$ and >1. The tunability of the cascaded responses is also explored in a series of proof-of-concept experiments, where a static response of a single-tap, incoherent loop filter is reconfigured by use of a Solc filter. In particular, it is demonstrated a reconfigurable single and dual-bandpass cascaded response, which can be further modified by changes in dispersion, spectral period of the slicing filter, central wavelength or spectral width of the broadband source, and apodization of the resonance. The results are compared with the predictions of the Gaussian model for the degradation of resonances in continuous-sample filters due to second-order dispersion.

1. Introduction

Due to their large bandwidth, discrete-time photonic signal processors constitute an attractive alternative to their electronic counterparts. In particular, transversal filters for the microwave band based on incoherent optical operation have been extensively explored. Microwave photonic filters (MPF) of this type can employ different architectures [1]. In single-source MPF (SS-MPF), the filter is based on the incoherent addition of an amplitude-modulated optical wave undergoing multiple delays, which are proportional to a basic period T determining the filter's spectral periodicity or free spectral range, $FSR = 1/T$. By contrast, in multiple-source MPF (MS-MPF) the delays are provided by a number of optical carriers at different wavelengths undergoing differential group delay in a dispersive medium.

A third architecture, which can be viewed as a limit case of MS-MPF, is the so-called continuous-sample MPF (CS-MPF) [1–11]. This architecture is based on broadband sources (BBS) consisting of a continuum of statistically independent and thus incoherent wavelengths. The name continuous-sample MPF follows from the observation that each independent wavelength represents a tap or sample in the MS-MPF architecture [6]. If the BBS optical spectrum is periodically-sliced before modulation the radio-frequency (RF) response shows resonances induced by the spectral periodicity. In the simplest case, a single sinusoidal modulation impressed onto the BBS spectrum allows for the implementation of a single RF resonance, which leads to the so-called single-bandpass CS-MPF [1–11].

An attractive way of enhancing the performance and tuning capabilities of MPF is to create architectures where the electrical-to-electrical response $H(\Omega)$ represents the product of two transfer functions, $H(\Omega) \sim H_1(\Omega)H_2(\Omega)$, thus providing an association in cascade [1]. However, it is difficult to obtain these associations because cascading requires specific conditions that guarantee that a certain combination of linear optical systems may represent a product in the RF domain. Conditions for cascading SS- and MS-MPF have been analyzed in detail in Ref. [12]. More recently, the possibility of cascading CS-MPF and SS-MPF has been recognized in Ref. [13] where a high-Q MPF was demonstrated by cascading a SS-MPF with comb response and a single-bandpass CS-MPF. The single resonance of the CS-MPF acts as a channel selector of the resonances in the periodic SS-MPF response because the cascaded filter operates in a regime where the 3 dB bandwidth Δf_{3dB} of the single CS-MPF resonance is slightly lower than the *FSR* of the SS-MPF.

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doi:10.1016/j.optcom.2009.11.074

As will be shown in this paper, neither the regime $\Delta f_{3dB}/FSR < 1$ nor the requirement of a single CS-MPF resonance represent the more general conditions for cascading CS/SS-MPF. In Section 2, we derive the condition that assures incoherent operation and cascading, Eq. (6) below, a condition that depends on MPF bandwidth. This fact contrasts to the usual incoherence condition of SS-MPF, where the only requirement is that the basic delay T be larger than the source's coherence time, a requirement that does not restrict the filter's bandwidth. In addition, we derive a lower bound for the ratio $\Delta f_{3dB}/FSR$ that shows the existence of two complementary regimes. When the cascade association is operated in the regime $\Delta f_{3dB}/FSR < 1$ this bound represents the minimum spectral feature in the SS-MPF response that can be selected by a CS-MPF resonance. By contrast, if the cascade is operated with $\Delta f_{3dB}/FSR > 1$, different CS-MPF resonances select bands composed of several SS-MPF channels, leading to multiple-bandpass responses.

In Section 3, we explore experimentally the tuning capabilities of the CS/SS-MPF cascade inherited from the CS-MPF resonances. In particular, we demonstrate the possibility of tuning compatible with the cascaded association through changes in width, position and shape of the CS-MPF resonance. These modifications are obtained by changing the dispersion value, the periodicity and form of the slicing filter; and the BBS width, shape and central frequency. Here we treat the SS-MPF as a static filter and, in fact, the SS-MPF in our cascaded filters is a simple loop filter based on a single T-delay and a cosine response. This arrangement allows for a simple visualization of the tunability of the cascaded structure. As for the CS-MPF spectral slicing filter we have used, for the first time to the best of our knowledge, a two-stage fiber Solc filter which permits imprinting two different spectral periods in the BBS optical spectrum. Finally, we end in Section 4 with our conclusions.

2. Condition for simultaneous incoherence and cascading

The general filter architecture analyzed in this paper is outlined in Fig. 1. It is composed of a broadband source (BBS) characterized by its optical spectral density $\mathbf{S}_0(\omega)$ [14, Section 4.3]. Its total power is given by $P_0 = \int \mathbf{S}_0(\omega)\, d\omega/2\pi$; its central optical frequency is:

$$\omega_0 = 2\pi v_0 = \frac{\int d\omega\, \omega \mathbf{S}_0^2(\omega)}{\int d\omega \mathbf{S}_0^2(\omega)}, \tag{1}$$

and its spectral width is:

$$\Delta v = \frac{\Delta\omega}{2\pi} = \frac{1}{\tau_{coh,0}} = \frac{P_0^2}{\int \frac{d\omega}{2\pi} \mathbf{S}_0^2(\omega)} = \left[\int \frac{d\omega}{2\pi} s_0^2(\omega)\right]^{-1}, \tag{2}$$

where $s_0(\omega) = \mathbf{S}_0(\omega + \omega_0)/P_0$ is the normalized spectral density shifted to the central frequency and $\tau_{coh,0}$ is the coherence time. If we denote by $e_0(t)$ the complex envelope, its (shifted) temporal degree of coherence is $\gamma_0(\tau) = \gamma_0(-\tau)^* = \langle e_0(t)^*\ e_0(t+\tau)\rangle/P_0$, which is, according to the Wiener–Kintchine theorem, the Fourier transform of the normalized shifted spectral density, $s_0(\omega)$. In terms of $\gamma_0(\tau)$ the coherence time in (2) is simply $\tau_{coh,0} = \int |\gamma_0(\tau)|^2\, d\tau$. Wave $e_0(t)$ is spectrally-sliced before modulation so that, if we denote by $H_{spec}(\omega)$ the optical transfer function of this filter, the optical spectral density of the wave $e_1(t)$ entering the modulator is $\mathbf{S}_1(\omega) = \mathbf{S}_0(\omega)\ \mathbf{T}(\omega)$, where $\mathbf{T}(\omega) = |H_{spec}(\omega)|^2$ is the filter's spectral transmittance. We denote by P_1 the optical power at the filter output so that $\alpha = P_1/P_0$ is the fraction of power transmitted by the filter. The definitions of the central frequency ω_1, the normalized spectral density $s_1(\omega)$, and the degree of coherence $\gamma_1(\tau)$ are parallel to those of the BBS before filtering.

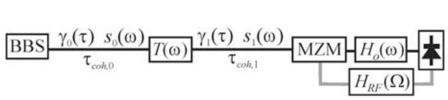

Fig. 1. System schematics. BBS: broadband source. MZM: Mach–Zehnder modulator. The remaining terminology is explained in the text.

The spectrally-sliced wave $e_1(t)$ is amplitude-modulated by use of a Mach–Zehnder electro-optic modulator, subsequently propagated in a linear optical system with transfer function $H_o(\omega)$, and detected with a photodiode of responsivity . The system RF transfer function is given by [6]:

$$H_{RF}(\Omega) = \sqrt{T_{RF}} \int \frac{d\omega}{2\pi} s_0(\omega) T(\omega) \times \frac{1}{2}\left[H_o(\omega)H_o^*(\omega - \Omega) + H_o(\omega + \Omega)H_o^*(\omega)\right] \tag{3}$$

where $T(\omega) = \mathbf{T}(\omega + \omega_0)$ is the shifted transmittance, $T_{RF} = [\pi Z \Re P_1/(2V_\pi)]^2$ is the RF gain, V_π is the modulator's half-wave voltage, $\Re$ is the detector's responsivity, and Z is the load impedance. The optical circuit considered in this paper is composed of the association of a dispersive line and a tapped delay line, whose transfer function is given by:

$$H_o(\Omega) = \exp(-j\phi\omega^2/2) \sum_{k=0}^{N-1} h_k \exp(-j\omega kT), \tag{4}$$

where $T = 1/FSR$ is the basic delay in the SS-MPF, h_k are the corresponding tap weights, and ϕ [ps^2/rad] is the total first-order dispersion. In (4) we have neglected any difference in dispersion caused by the SS-MPF.

Substituting (4) in (3) and using also that the complex degree of coherence $\gamma_1(\tau)$ is the Fourier transform of the normalized spectrum, $s_1(\omega) = \int \gamma_1(\tau) \exp(-j\omega\tau) d\tau$, we get:

$$H_{RF}(\Omega) = \sqrt{T_{RF}} \sum_{k,p=0}^{N-1} \frac{1}{2} h_k h_p^* \exp(-j\Omega pT) \times \left[\exp(-j\phi\Omega^2/2)\gamma_1(-\phi\Omega - (k-p)T) + \exp(+j\phi\Omega^2/2)\gamma_1(-\phi\Omega + (k-p)T)\right] \tag{5}$$

We now denote by $\tau_{coh,1}$ the coherence time associated to the complex degree of freedom $\gamma_1(\tau)$, so that $\gamma_1(\tau) = 0$ for $|\tau| > \tau_{coh,1}$. Then, for $|-\phi\Omega \pm (k\text{-}p)T| > \tau_{coh,1}$ the corresponding terms in (5) vanish, as is sketched in Fig. 2. Using now that $\Omega < 2\pi B_{RF}$ where B_{RF} is the MPF's bandwidth, it follows that if

$$T > \tau_{coh,1} + 2\pi|\phi|B_{RF}, \tag{6}$$

all terms with $k \neq p$ in the double sum in (5) vanish, and the transfer function reduces to a product of transfer functions: $H_{RF}(\Omega) = \sqrt{T_{RF}} H_1(\Omega)H_2(\Omega)$, where the first transfer function corresponds to the CS-MPF:

$$H_1(\Omega) = \cos(\phi\Omega^2/2)\gamma_1(-\phi\Omega) \tag{7}$$

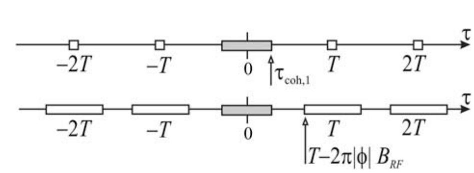

Fig. 2. Derivation of the condition for both incoherence and cascading. Above: in absence of dispersion, the arguments of functions γ_1 in (5) are multiples of T. The support of $\gamma_1(\tau)$ is depicted with a shaded region. Below: with dispersion, the arguments lie within an interval of length $2 \times 2\pi\,|\phi|B_{RF}$.