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Flat-top ultra-wideband photonic filters based on mutual coherence function synthesis

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Abstract

A novel all-incoherent optical circuit that allows for band-pass microwave-photonic filter design is presented and verified through numerical simulation. In contrast to conventional spectrum-sliced optical architectures that operate on the basis of a finite number of discrete taps, our proposal is based on arbitrary shaping of the spectrum of the broadband optical source in a conventional frequency encoder. This fact dramatically increases the free spectral range of the filter with respect to the conventional discrete-time optical processing. The filter transfer function is given by the mutual coherence function of the filtered source which allows, through an inverse problem, sculpting the RF filter response. The effect of higher-order dispersion terms is also included by means of the optical coherence theory. Finally, some strategies are provided in order to alleviate the baseband resonance constraint. Numerical results are also included.

Keywords: Optical signal processing; Optoelectronic devices

1. Introduction

Processing microwave signals in the optical domain offers several advantages in comparison with the electrical approach. We point out flexible and reconfigurable filter design, immunity to electromagnetic interference and frequency-dependent losses, large bandwidth to overcome the electronic bottleneck, high-speed processing capability, and potential full-integration with radio-over-fiber technology. In a typical microwave-photonic processor, the input electrical signal to be filtered is transferred to the optical domain via an electro-optic device that modulates the radiation coming from an optical source. After that, light is fed to an optical circuit and, finally, the processed signal is converted back to the electrical domain by means of a high-speed photodiode that provides the output [1–3].

Many different approaches to microwave-photonic filter design based on tapped digital filters have been demonstrated [1–3]. The key idea is the summation of a series of delayed identical optical signals that act as the tap elements in the discrete-time signal processor. The discrete nature of the filtering operation imposes a periodic response for the microwave transfer function that physically restricts the bandwidth of the signals to be processed. In this direction, most experimental realizations provide free spectral ranges (FSRs) of only several GHz. Both single-source and multiple-source have been employed to excite the optical circuit. In this direction, lower cost alternatives employ a broadband optical source sliced by different optical components, such as fiber Bragg gratings [4–7], acustooptical modulators [8], or arrayed waveguide gratings [9]. Further, wavelength division multiplexing channel selectors can be employed for performing the spectral-shaping [10].

Usually, the coherence time of the optical source (τ_C) is shorter than the minimum time delay (T) between the taps in order to ensure incoherent operation [11,12]. This condition guarantees that the filter has negligible sensitivity to changes in environmental conditions. In principle only filters with positive coefficients can be implemented in the

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incoherent regime, which prevent from band-pass filtering. However, this limitation has been overcome in the past few years [13–18]. From a practical point of view, the realization of filters with large number of taps and large FSR constitutes an important direction in incoherent microwave-photonic filter research [6,7,18,19]. This fact implies a serious practical drawback requiring the implementation small tap delays with sufficient precision.

A completely different strategy based on filter design with a continuous, non-discrete, weight distribution has been proposed in the past year to deal with this matter. These filters are based on pulse-shaping techniques and, in contrast to the traditional tapped delay-line approach, allow higher operating bandwidths, providing the convenient framework for high-bandwidth, user-defined filter implementation. Two different approaches were adopted in the past year to tackle this matter operating either in the coherent [20,21] or in the incoherent regime [22,23].

In the coherent regime [20,21], synthesis of arbitrary microwave-photonic amplitude filters is performed by using a tunable laser optical carrier passed through a Mach-Zehnder intensity modulator (MZM) driven by the microwave input signal and a programmable pulse-shaping geometry. From a practical point of view, the bandwidth of the RF filter is limited by the FSR of the spectral disperser in the pulse shaper, whereas the finest spectral feature is equal to the optical spectral resolution. A virtually image phased array (VIPA) provides both a large FSR (50 GHz) and a high spectral resolution (0.7 GHz). However, the above device is limited to work on a highly coherent optical source which limits practical applications.

In another approach [22,23], the microwave filter is based on a MZ fiber interferometer illuminated with a broadband spectrally incoherent source and a group-delay-dispersion (GDD) circuit with a bandwidth exceeding that of the optical source. Here, the filter response shows a low-pass filtering region in addition to two band-pass zones centered at frequencies determined by the GDD coefficient and the optical path length difference through the arms of the MZ interferometer. Although, this fact allows tuning the operating region, in all bands, the spectral response is provided by the Fourier transform of the spectral density function (SDF) of the source which is assumed to be Gaussian. This fact drastically limits the possibility to tailor the filter amplitude response. In contrast to [20,21], the optical circuit is operated in the incoherent regime, ensuring a robust behavior.

Here, for the first-time, we propose a novel optical device to implement microwave-photonic optical filters based on an incoherent spectral-shaping geometry. In contrast to [22,23], the SDF of the broadband spectrally incoherent source is arbitrarily sculpted by means of a user-defined multiplicative real and positive filter function implemented through spectral encoding of the source [24]. In this way, the use of a SDF different from the modulated Gaussian function [22,23] is proposed for the first time. We emphasize the non-discrete nature of the filter function which drastically differentiates our proposal with respect to the vast class of conventional discrete-time optical processors based on tapped digital filters implemented through discrete spectrum-slicing.

The filtering stage could be implemented by use of a spatial light modulator in a reflective spectral-shaping geometry. This device has been used with high efficiency by several researchers for temporal shaping of short pulses [25]. We note that the use of a spatial light modulator as a spectral-encoder permits reconfigurability with a high versatility and operation speeds at kHz rates. The filtered source is subsequently modulated in the temporal domain by the microwave signal to be processed. Concerning modulation formats, both double-sideband (DSB) and single sideband (SSB), are allowed. Further, phase modulation (PM) in the low-voltage modulation regime is also permitted. Again, after signal propagation in a broadband group-delay-dispersion (GDD) circuit and subsequent photodetection, we recognize that the mutual coherence function (MCF) of the filtered source becomes the filter transfer function. It is worth mentioning that for our optical proposal the FSR and the minimum feature size of the optical filter determine, respectively, the minimum feature size and the maximum bandwidth of the RF filter.

In this paper, we present a compact analytical result, irrespective of the form for the SDF of the broadband source. Due to the incoherent regime of operation, the optical device performs a low-pass filtering operation. To deal with this matter, here we adopt an approach based on a simple algorithm working on the MCF of the filtered source. We note that a similar algorithm has been developed in the context of radio-frequency spectral-shaping of ultra-wideband (UWB) signals [26]. The scaling properties of the RF filter are fully controlled through the dispersion coefficient of the GDD circuit. It should be mentioned that, in a different context, this optical circuit was proposed for arbitrary waveform generation in the microwave and millimeter-wave region [27,28]. Finally, a numerical example concerning the design of an optical band-pass filter with sharp edges for the UWB region is included. These signals have an unprecedented opportunity to impact communication systems. According to the Federal Communications Commission, the UWB spectrum is allocated between the 3.1 and 10.6 GHz interval, by far the largest allocation of bandwidth to any commercial system. This 7.5 GHz interval promises substantial applications in radio communications, as well as in radar, safety, and biomedicine.

2. Optical setup

Our proposal is illustrated in Fig. 1. The broadband optical source is spectrally incoherent. From an experimental point of view, either an amplified spontaneous emission (ASE) source or a superluminescent LED may be employed. The source is filtered in the spectral domain by means of a multiplicative filter function. The filtering stage in the optical domain is implemented by means of a