Separate Carrier Tuning Scheme for Integrated Optical Delay Lines in Photonic Beamformers

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***Abstract*—We implement and experimentally demonstrate the separate carrier tuning technique on an optical ring resonator-based integrated optical delay line. For the first time, the carrier tuner, the delay elements and the optical sideband filter are integrated on the same chip. The proposed approach allows to reduce the complexity of the delay unit and makes the bandwidth independent of the absolute RF frequency. The demonstrated principle can be conveniently employed in any integrated non-coherent optical beamformer system.**

***Keywords*—optical delay lines; tunable delay; optical beamforming; phased arrays; resonators; microwave photonics.**

I. Introduction

In recent years, the use of photonic technology for control of phased array antennas has been proposed as an attractive solution in the cases where high performance in terms of bandwidth, multibeam capability or fast reconfigurable operation are needed [1]. Several authors have proposed and demonstrated the advantages that can be obtained by employing integrated variable optical delay lines (ODL) based on integrated optical ring resonators (ORR) for true time delay (TTD) control of phased arrays: large instantaneous bandwidth, continuous delay tunability and high compactness are given by the integrated photonic approach [2-5]. In some cases, all this can be achieved with low loss (as low as 0.2 dB/cm with a waveguide bending radius of 125 µm, as reported in [6]), which is a particularly important aspect in the common practical situation where the optical beam former (OBFN) is placed in the front-end of low noise receiver systems, as in the case of application of phased arrays to satellite signal reception or radio astronomy.

In [7, 8] we have proposed and demonstrated a beamformer based on ORRs delay units. The system is based on an optical single sideband suppressed carrier (OSSB-SC) modulation scheme, which allows to reduce the required delay bandwidth to the one of a single sideband, with advantages in terms of reduced complexity for the delay units. This technique implements a *coherent* beamformer approach: it requires a single laser source, where a portion of the light is tapped out and used for carrier reinsertion before direct detection can be realized.

In a variety of cases, an *incoherent* beamforming approach could be of interest, for example for the possibility of employing multiple laser sources instead of a single one, direct modulation instead of external modulation, or to use separate carrier wavelengths to implement a wavelength division multiplexing (WDM)-based beamformer as proposed for example in [9] (Fig. 1). In non-coherent optical systems, however, the OSSB-SC operation with single carrier re-insertion described in [7], used to simplify the complexity of the delay units, can no longer be used, due to the fact that the separate signals do not share the same coherent carrier any longer.

The separate carrier tuning (SCT) technique proposed in several recent works [4, 10] appears as an ideal solution for the delay elements to be employed in all the cases where a non-coherent OBFN is used, in order to keep the advantage, in terms of ODL complexity reduction given by the SSB modulation, and still allowing the use of a simple unbalanced detector.

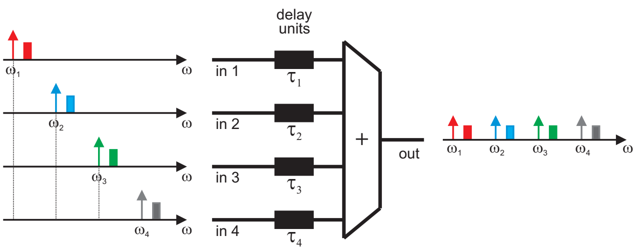

Figure 1. Example of a non-coherent OBFN based on WDM

In this paper, after a theoretical introduction on the SCT technique (Section II), we describe the implementation of a SCT delay unit (Section III) in which the carrier tuner (CT), the delay element and the optical sideband filter (OSBF), used to generate the optical single sideband full carrier (OSSB-FC) modulation, are integrated on the same optical chip. In Section IV we demonstrate its functionality in terms of generation of SSB modulation, full-2π carrier phase shift and continuously tunable delay. This type of delay unit will be employed in a WDM-based incoherent beamformer as proposed in [9].

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II. THEORY OF OPERATION

A. *Separate Carrier Tuning Technique*

The theory at the basis of the SCT technique is clearly explained in [4] and in [10], respectively describing its application to delay lines based on ORRs and on stimulated Brillouin scattering in optical fibers. The importance of this technique comes from the fact that, for an OSSB-FC modulated signal, it allows to reduce the requirement of the linear dispersion characteristic, needed for TTD operation of a delay line, only to the band which is actually occupied by the sideband. This is possible by *separately* applying to the carrier the same phase shift that it would experience when an ideal delay unit, having a linear phase slope over the whole frequency range, would be employed (Fig. 2). The two required dispersive characteristics, localized at different frequencies, can be induced by tunable optical resonances given by two different, independently-tunable optical structures. This has the additional advantage of making the TTD operation independent from the central frequency of the modulated RF signal.

The phase shift adjustment to be applied to the carrier angular frequency ω_C can be computed as in [10] or [4]. Let us consider an OSSB-FC modulation where only the upper sideband is kept, as in Fig. 2. The group delay T_{group} applied to the signal at frequency $\omega_c + \omega_{RF}$ is given by the slope of the optical phase characteristic at the same frequency:

$$T_{group} = \left. \frac{\partial \varphi(\omega)}{\partial \omega} \right|_{\omega_c + \omega_{RF}} \tag{1}$$

For TTD operation, the RF phase should be a linear function of frequency over the whole frequency range [4], with slope T_{group}. The desired carrier phase should then be

$$\varphi(\omega_c) = \varphi(\omega_c + \omega_{RF}) - \omega_{RF} \left. \frac{\partial \varphi(\omega)}{\partial \omega} \right|_{\omega_c + \omega_{RF}} \tag{2}$$

If a dispersive device is used to add a constant phase slope to the sideband, as in (1), the carrier phase will assume a certain value φ. To achieve TTD operation, the carrier phase should be adjusted to the value given by (2), by adding a phase shift to the carrier equal to

$$\Delta\varphi_{carrier} = \varphi(\omega_c) - \varphi \quad (\text{mod } 2\pi) \leq 2\pi \tag{3}$$

The carrier phase adjustment can be applied modulus 2π since the carrier is monochromatic [10].

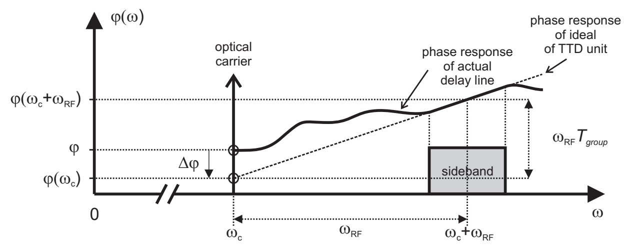

Figure 2. Principle of operation of an optical true time delay unit with separate carrier tuning. The phase of the optical carrier has to be compensated by a phase shift as given by (3).

In the next paragraph, we will describe how to achieve carrier tuning using optical ring resonators.

B. *Carrier Tuning employing Integrated Ring Resonators*

An optical ring resonator is a structural slow-light device, with a frequency-localized dispersive behavior characterized by a 2π optical phase transition centered at the resonant wavelength of the ring [2, 7] (Fig. 3). In the vicinity of the resonance, the phase shift is approximately linear.

The dispersion property given by the ORR structure can be effectively employed to provide the optical carrier, in the OSSB-FC modulation scheme described previously, with the desired phase shift required to implement the SCT technique. By simply detuning the resonant frequency of the ORR around the carrier wavelength, it is possible to give the carrier the desired phase shift as in (3).

Using two optical ring resonators allows to achieve a sharp transition in the phase transfer around the resonance frequency. This permits, when required, to have a complete 2π phase shift with limited detuning of the resonant frequency, thus limiting the dispersion effects only in the vicinity of the desired wavelength, without sensibly affecting the phase transfer in the spectral region occupied by the sideband (Fig. 3). In fact, in this SCT scheme, it is desired that the dispersion at the sideband can be tuned independently, using a separate delay structure, in order to impose the required amount of RF delay.

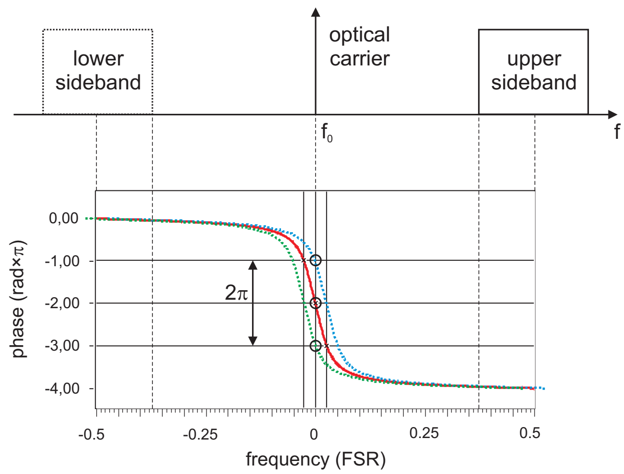

Figure 3. Phase response of a double ORR filter structure. The circles indicate the phase transfer experienced by the carrier for the three different resonance positions.

Based on this theory, we propose a delay structure employing the SCT technique, consisting of: *a*) *filter* (OSBF), used to generate OSSB-FC modulation by removing one sideband from a double-sideband full carrier signal; *b*) *delay unit* employing 2 ORRs, operated as described in [7, 8]; *c*) *carrier tuner*, also consisting of 2 ORRs.

III. SYSTEM SETUP

A. *Chip Layout*

The schematic of the SCT delay unit is shown in Fig. 4. This structure is a section of an existing integrated photonic chip, realized on low loss TriPleX technology, implementing a fully-programmable optical beamformer which has been reported in [8]. An appropriate individual signal path of the chip was isolated and connected to the measurement setup. This selected signal path contains 4 ORRs and an optical filter used to realize the OSSB modulation. The IIR filter used for the demonstration of OSSB generation is of the "Mach-Zehnder interferometer (MZI) + ring" type. Two of the ORRs are used as CT unit, while the other two rings implement the delay. The detailed layout of the employed chip can be found in [8].

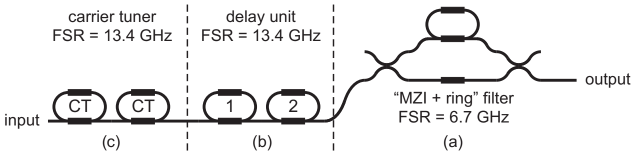

Figure 4. Schematic of the delay structure employed to demonstrate the single-chip SCT-based delay unit: (a) filter; (b) delay unit; (c) CT

B. *Measurement Setup*

The measurement setup (Fig. 5) is described below. An EM4 high power laser generates a 100 mW optical carrier, which is modulated using an Avanex FA20 Mach-Zehnder modulator (MZM) by the RF signal generated at port 1 of an Agilent N5230A vector network analyzer (VNA). The double sideband (DSB) modulated signal is fed to the optical chip whose schematic was shown in Fig. 4. The chip is thermo-optically programmed to filter out the lower sideband and to implement the variable SCT delay. An EDFA is inserted before the detector (Discovery Semiconductor DSC 710) to compensate for the fiber-chip coupling losses, which will be reduced in future implementations by integrating suitable spot-size converters. The RF output of the detector is connected to port 2 of the VNA for the amplitude and phase measurements.

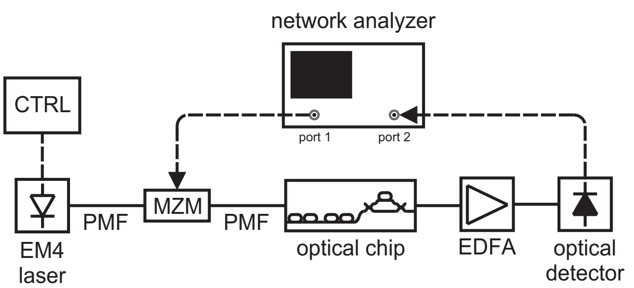

Figure 5. Schematic of the measurement setup. Polarization maintaining optical fibers (PMF) are used for the interconnection of laser, modulator and optical chip.

IV. EXPERIMENTAL DEMONSTRATION

In this section we demonstrate the functionality of the SCT delay structure by individually analyzing the performance of the filter, the delay unit and the CT section.

A. *Filter Response for OSSB-FC Operation*

Fig. 6 shows the measured magnitude response of the MZI + ring filter (Fig. 4a), in comparison with the spectrum of the signal to be processed. In order to display the optical response of the filter on the VNA, the phase shift method [11] has been used, employing a 10 MHz modulating tone and sweeping the optical carrier wavelength over the band of interest. Assuming an optical suppression of 25 dB (corresponding to 50 dB in RF) for the undesired sideband, the usable bandwidth in which it is possible to achieve OSSB-FC modulation for the RF signal results to be between 1.2 GHz and 2.2 GHz (Fig. 6).

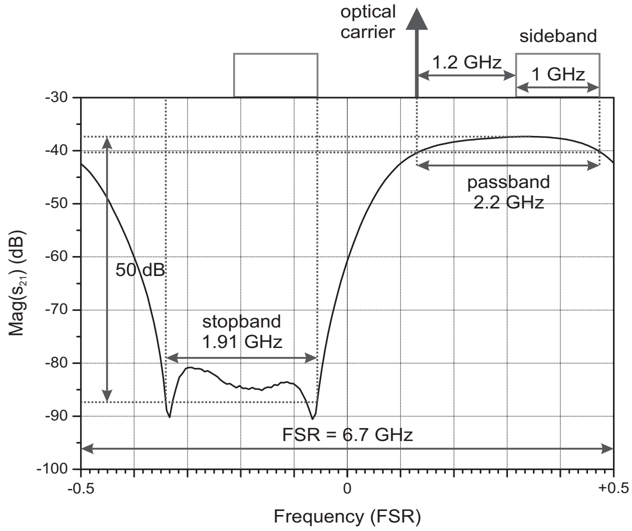

Figure 6. Measured magnitude response of the OSBF used to suppress the undesired sideband of the optically-modulated RF signal

B. *Delay unit: RF Phase Responses*

The ORRs composing the delay unit section of the chip (Fig. 4b) can be tuned in such a way to achieve a linear slope (which corresponds to a constant delay) for their phase characteristic, over the signal band occupied by the sideband that is left after the transit through the OSBF (Fig. 6). The amount of required delay, according to (2), is proportional to the phase slope, which can be varied with continuity by properly tuning the ORRs of the delay section, using the same procedure that has been described in [8]. In Fig. 7, the four measured delay characteristics show good matching with their theoretical responses.

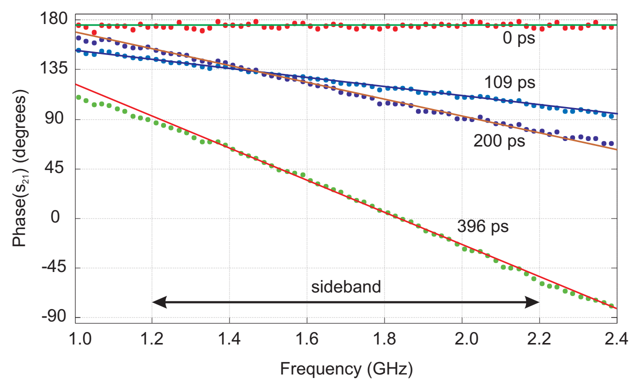

Figure 7. Measured (dotted) and theoretical (solid) phase responses at the signal sideband: different slopes correspond to different delays

C. *Carrier Tuner: 2π Phase Shift*

In order to demonstrate the effectiveness of the carrier tuning unit in Fig. 4c, we show measured RF phase characteristics on the detected sideband. In fact, in a SSB plus carrier modulation scheme, the phase shift imparted on the optical carrier generates an equal phase shift on the detected electrical signal, and which is constant with the RF frequency. An experimental demonstration of this principle is given in Fig. 8 by using the carrier tuning unit in Fig. 4c. Fig. 8 shows the effect, on the RF signal at the output of the detector, when a variable phase shift between 0 and 2π is imposed to the optical carrier via the ORRs of the CT unit, tuned employing the scheme shown in Fig. 3. The constant phase shift over the detected sideband shows that the carrier phase is effectively being shifted over the whole 2π range, and the fact that the slope does not change confirms that the carrier phase can be tuned without affecting the linear phase response at the delay band (Fig. 3).

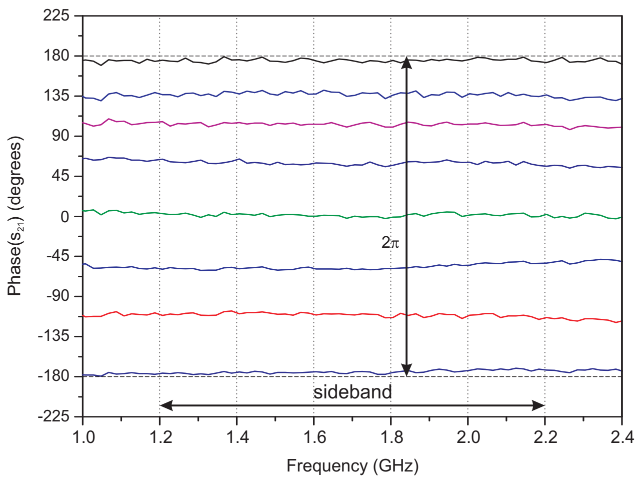

Figure 8. Phase shift of the RF phase responses. A phase shift over 2π is achieved by changing the phase of the optical carrier. The constant slope shows that the amount of delay is not influenced by the carrier tuning. For ease of comparison, the phase responses have been made horizontal by applying to each of them the same amount of slope offset, using the electrical delay function of the network analyzer.

V. Conclusions

In this paper we experimentally demonstrated the operation, over a bandwidth in excess of 1 GHz, of an optical delay line based on optical ring resonators employing the separate carrier tuning principle. For the first time in this type of approach, the carrier tuner, the delay elements and the optical filter are integrated on a single photonic chip with low waveguide loss, using the same basic building blocks employed in the beamforming chip described in [7, 8]. The bandwidth and the absolute frequency of the RF signal are only limited by the reuse of this pre-existing filter, which was designed to operate in a different mode [8], and not by the selected approach. A filter with wider band and selectivity is currently being realized in order to achieve delay over much larger instantaneous bandwidth and with higher RF frequencies. The demonstrated system will be optimized in bandwidth and achievable delay to be employed in a wide band WDM-based integrated photonic beamformer.

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