CMOS-compatible Integrated Optical Delay Line for Broadband K_u-band Satellite Communications

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Abstract—We present the first demonstration of a broadband and continuously tunable integrated optical true-time-delay line, operating over the complete DVB-S satellite communication band, realized with a CMOS-compatible TriPleX™ waveguide technology. The integrated optical chip includes a delay line and an optical sideband filter (OSBF) based on reconfigurable optical ring resonators (ORR). The filter and the delay responses are software programmable and have been configured for K_u-band operation. For the first time, the continuous tunability between 0 and 277 ps is demonstrated over the complete for DVB-S satellite communication band (10.7-12.75 GHz).

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

I. INTRODUCTION

Continuously tunable and broadband true-time-delay (TTD) lines are of primary interest in many applications of electronics and photonics for modern communication systems. Applications like phased array antennas [1], filtering of microwave and mm-wave signals [2, 3], and generation and shaping of ultrawideband pulses [4, 5], are some examples where broadband TTD is necessary. Those applications also require that the TTD is continuously tunable and capable of processing high-frequency microwave signals.

Purely electronic solutions exist since many years, but usually offer either narrowband performance, limited amount of delay or discrete delay levels, in addition to a limitation in the RF frequency that can be processed. For this reason researchers have started to propose *photonic* solutions [1, 6] to overcome those limitations and implement TTDs capable of offering all the desirable characteristics *simultaneously*. Nonetheless, the proposed optical solutions are often based on optical fibers and discrete optical components, or free-space optics, and are bulky and expensive.

In [6, 7] we proposed a broadband and continuously tunable delay line, *integrated* on a single photonic chip, realized with a CMOS compatible process [7]. The

integrated solution provides a much higher compactness and better performance than a fiber-based approach and, as the processing is performed with CMOS compatible fabrication equipment, the associated costs can be very limited. This delay unit includes multiple delay lines based on optical ring resonators (ORR), combiners, and an optical sideband filter (OSBF) used to generate optical single-sideband modulation (OSSB). The chip was designed for application to DVB-S satellite reception [6, 8], and demonstrated antenna beamforming processing after downconversion from K_u-band to L-band (1-2 GHz) [7].

In this paper, we demonstrate the *reconfigurability* of the chip and the capability of processing RF signals directly at K_u-band, without need for prior downconversion, using the same device. In fact, the ORRs can be programmed to provide broadband delay over an arbitrary frequency band. In addition to that, the optical filter offers a frequency-periodic response that has also been used at the advantage of reconfigurability. This principle can also be employed for processing multiple bands *simultaneously*, as for example in multi-wavelength optical signal processors, e.g. incoherent microwave photonic filters (MPF) [2, 3] or beamformers [9].

The paper is organized as follows. Section II introduces the theory of ORR-based TTDs and the employed modulation techniques. Section III describes the chip layout and the measurement setup. In Section IV the experimental results are displayed and discussed. Section V gives the conclusions.

II. THEORY

A. Reconfigurable Passband Optical Delay Lines based on ORR Filters

The principle of implementing true-time-delay using optical ring resonators (ORR)-based optical filters has been first proposed by Rasras et al. [10] and demonstrated in several configurations [6, 7].

The group delay T_{group} at $\omega_c + \omega_{RF}$ is defined as the phase slope at the same frequency point:

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

The principle consists in creating an approximately linear phase response, with respect to frequency, over the band of interest, using the 360 degrees phase transition offered by ORR filters around their resonance frequency [6].

B. Optical Modulation and Delay Generation Technique

With a fixed number of ORRs, a tradeoff exists between the delay bandwidth and the amount of delay that can be generated with a maximum acceptable phase error. This bandwidth-delay limitation can be overcome by limiting the required delay bandwidth by employing optical single-sideband modulation, either using carrier suppression, reinsertion and balanced detection, as in [6], or full carrier and direct detection [11]. In this way it is possible to limit the bandwidth requirement of the desired linear phase characteristic only over the sideband instead, and still providing the correct group delay to the information signal modulating the optical carrier. In this experiment we generate OSSB-FC by employing an optical sideband filter (OSBF) to suppress one of the sidebands of an intensity modulated (IM) optical carrier. The carrier and the desired passband are passed through the filter passband. Then it is possible to configure the ORR responses to generate delay over the remaining sideband (Fig. 1).

Figure 1. Principle of operation of the optical true time delay unit. One sideband (LSB in figure) is suppressed using a passband filter (dashed line). The optical carrier and the remaining sideband are set in the filter passband. The tunable delay is applied to the remaining sideband by tuning the response (red solid line) of one or more optical ring resonators.

The RF phase shift provided to the information signal can be controlled either in the electrical domain, e.g. using a broadband RF phase shifter, or directly in the optical domain, e.g. using the separate carrier phase tuning principle as demonstrated in [11, 12].

III. SYSTEM SETUP

A. Schematic Chip Layout

The schematic of the delay unit is shown in Fig. 2. This structure has been realized on low loss TriPleX™ waveguide technology [13], described in more detail in [8]. A specific input-output signal path can be selected by programming the tunable couplers of the chip, and was connected to the measurement setup, as shown in Fig. 3. This selected path contains 4 ORRs, used to create the phase slope required for the desired delay, as in Eq. 1, and an optical filter used to realize the OSSB-FC modulation, as previously discussed. The filter is of the type Mach-Zehnder interferometer (MZI) + ring. In [7] the

detailed layout of the microwave photonic chip has been described.

Figure 2. Schematic of the delay unit: delay line based on 4 cascaded ORRs (a); filter structure employed to generate the optical single-sideband modulation with full carrier (OSSB-FC) (b).

B. Measurement Setup

Fig. 3 shows the employed measurement setup. An EM4 high-power laser (100 mW maximum optical power) produces the optical carrier in the 1550 nm band, which is intensity modulated (IM) using an Avanex FA20 Mach-Zehnder modulator (MZM), biased in quadrature. The RF modulating signal is generated by an Agilent N5230A vector network analyzer (VNA). The IM signal is fed to the optical chip whose schematic was shown in Fig. 2. The chip is thermo-optically programmed to filter out the lower sideband and to implement the variable delay, as graphically shown in Fig. 1. An erbium-doped fiber amplifier (EDFA) is used to compensate for the fiber-to-chip coupling losses, which will be reduced in future implementations by integrating suitable spot-size converters. The amplified signal enters a Discovery Semiconductor DSC 710 high-power photodetector (PD). The RF output of the detector is connected to port 2 of the VNA for the amplitude and phase measurements.

Figure 3. Schematic of the measurement setup. Polarization maintaining fibers (PMF) are used for the optical interconnections between laser, modulator and optical chip.

IV. EXPERIMENTAL DEMONSTRATION

In this section we demonstrate the functionality of the tunable Ku-band delay unit by analyzing first the performance of the OSBF used to suppress the LSB, and then the magnitude and phase responses generated on the remaining sideband when the tunable ORR delay line is cascaded to the OSBF.

A. Filter Response and Wavelength Settings for OSSB-FC Operation

In Fig. 4 we show the measured magnitude and phase responses of the optical sideband filter, in comparison with the IM signal to be processed. The phase shift method [14]

has been employed to display magnitude and phase of the optical response of the filter on the VNA. A 50 MHz modulating tone is produced by port 1 of the VNA and the optical carrier wavelength is swept over the band of interest.

The frequency response of the OSBF repeats periodically every FSR, which for this filter is approximately 6.7 GHz. By properly tuning the wavelength of the optical carrier, as shown in Fig. 4, it is possible to make sure that the unwanted sideband falls in one of the stopbands of the OSBF, while the desired sideband passes undistorted through one of the passbands. The optical carrier is also passed through one passband (see Fig. 4, top). In this way the periodicity of the OSBF was employed to generate OSSB-FC over an RF signal in the DVB-S band 10.7-12.75 GHz.

From Fig. 4 it can be noticed that the suppression in the OSBF stopbands varies across frequency. This can be attributed to the group index change in the bends of the ORR included in one of the interferometer arms of the filter [15, 16]. Nonetheless, the tunability of the OSBF allowed to reconfigure the response in such a way to obtain maximum suppression over the undesired stopband, that is, between 10.7 GHz and 12.75 GHz below the carrier frequency (Fig. 4, top).

Figure 4. Measured magnitude response of the OSBF used to suppress the undesired sideband of the optically-modulated RF signal (the remaining sideband and the carrier are not suppressed). Note the high flatness (± 2.5 deg) of the phase characteristic over the passband.

B. Delay unit: RF Amplitude and Phase Responses

Once the lower sideband is suppressed by proper choice of the laser wavelength (Fig 4), the ORRs in the delay line section of the chip (Fig. 2a) can be tuned in such a way to achieve a linear phase slope - i.e. a constant delay - over the signal band occupied by the upper sideband, left after the transit through the OSBF. According to Eq. (1), the

amount of delay is proportional to the phase slope, which in turn can be varied with continuity by properly tuning the ORRs of the delay section (see [7] for more details on the delay tuning procedure). Fig. 5 shows the achieved RF magnitude and phase responses of the delay line, in the 10.7-12.75 GHz band, for different delay settings.

Figure 5. Measured magnitude (top) and phase (bottom) responses of the proposed delay unit at Ku-band, for 4 delay settings. Different phase slopes correspond to different delays.

The measured phase characteristics show good matching with their theoretical linear responses. The magnitude responses have been normalized with respect to the magnitude response (link gain) of the analog photonic link (APL) obtained by removing the optical chip from the setup in Fig. 3, and connecting the MZM directly to the EDFA. In this way, it has been possible to exclude from the measurement the effects of the frequency response of the optical components. The amplitude ripple in band for the 0 ps trace is below 5 dB. The existence of an amplitude ripple can be attributed to a non-perfectly flat response of the filter passband. The other responses show an attenuation that increases when increasing the delay, as expected due to the longer propagation time in the waveguide.

V. CONCLUSIONS

We experimentally demonstrated, for the first time, broadband and continuously tunable group delay generation using an integrated optical true-time-delay line, over the complete DVB-S satellite communication band. The delay line was designed to operate both in Ku-band and in L-band and realized in CMOS compatible waveguide technology. This work demonstrates the

capability of processing RF signals directly at K_u -band, without need for prior downconversion, thanks to the *reconfigurability* of the optical chip based on ring resonators.

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