Microwave photonics beamformer based on ring resonators and arrayed waveguide gratings

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***Abstract*—In this paper a novel microwave photonics beamformer device concept, for single side band (SSB) modulated signals, is presented. The device is based on tunable lasers, arrayed waveguide gratings and an all-pass ring resonator. The reconfiguration accuracy and time depend on the laser switching characteristics.**

I. Introduction

Microwave photonics is becoming a strong field where the processing of high frequency microwave signals is done completely in the optical domain [1], avoiding the common limitations of the electric domain. Amongst the applications, beamforming is of great interest. On the other hand, integrated optics ring resonators (RR) are key devices due to their small foot print and filtering response. Several approaches exist in the literature for optically controlled tunable beamformers, amongst them some using all-pass RR. In the work by Adams et al. [2] tunability is done by means of the thermo-optic effect with heaters. Chang et al. [3] use the thermal nonlinear effect of Silicon. However, despite the change in refractive index with the temperature can be large (for instance in Silicon [4] $\partial n/\partial T = 1.86 \cdot 10^{-4} K^{-1}$), the response times are not better than 1 μs [5]. The approach presented in this paper is limited by the switching speed of the tunable lasers, which are well below the nanosecond scale [6].

II. Microwave phase shifter

Consider a single-side band (SSB) optical signal, with optical carrier frequency f_c and radio frequency (RF) f_{RF}. The signal is filtered using an all-pass ring-resonator, hence a relative phase shift is induced between the optical carrier and the RF sub-carrier frequencies [7]. The RR response is periodic, hence the phase shift depends on both the position of the optical carrier within the spectral period (Free Spectral Range, FSR) and the relative difference between the optical carrier and RF sub-carrier frequencies. The characterization of a RR limited to two FSR span is shown in Fig. 1. For a given optical carrier and accompanying RF sub-carrier, by tuning the former, the relative phase shift changes, due to the shape of the phase response of the all-pass RR. A power penalty takes place, due to the non-flat power transfer function in practical devices as in Fig. 1. The penalty depends on the RR coupling constant and round trip losses.

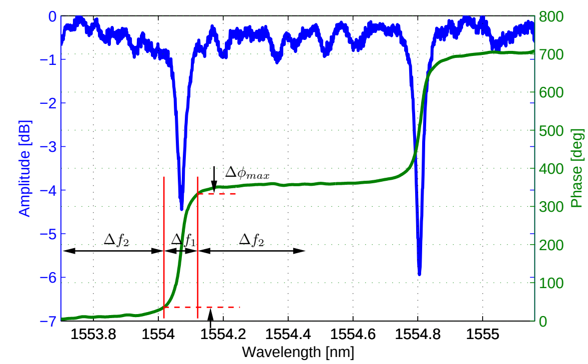

Fig. 1: Power transmission and phase characterization of an all-pass single RR in two FSRs.

III. Tunable beamformer concept

The beamformer device is depicted in Fig. 2 and consists of N tunable lasers multiplexed by an Nx1 AWG. The lasers are externally modulated by a dual-drive Mach Zender Modulator (MZM), filtered with an all-pass RR and then demultiplexed by an 1xN AWG. The phase shift for each antenna can be selected by tuning the corresponding laser in the range allowed by the passband of the AWG, and within the RR FSR. The spectral response of the all-pass RR is periodic with period $FSR = \dfrac{c}{n_g L_c}$, where c is the speed of light in vacuum, n_g is the group refractive index of the waveguides and L_c the RR cavity length. For the phase shifter design it is useful to partition the RR FSR as shown in Fig. 1. The maximum phase shift ($\Delta\phi_{max}$ in the figure) is given by both a) the spectral separation of the optical and RF signals and b) the phase response slope. From the figure, to be able to change $\Delta\phi$ in the range [0,$\Delta\phi_{max}$] by tuning the laser, $\Delta f_1 \leq f_{RF} \leq \Delta f_2$. The pair $\Delta\phi_{max}$ and Δf_1 depends on the slope of the phase transfer function around resonance. This slope depends on the power coupling constant K between the ring and the access waveguide. The lower the K value, the higher the slope, and the wider the flat regions in the phase transfer, out of resonance [8]. A steep slope turns into a small fraction of the FSR (Δf_1) needed to attain the targeted maximum phase shift ($\Delta\phi_{max}$). The maximum achievable phase shift for a single ring device will be always lower than 360 degrees with this configuration, but this can be solved by using multistage

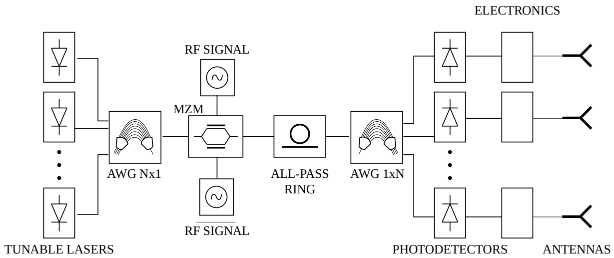

Fig. 2: Schematic of the integrated beamformer.

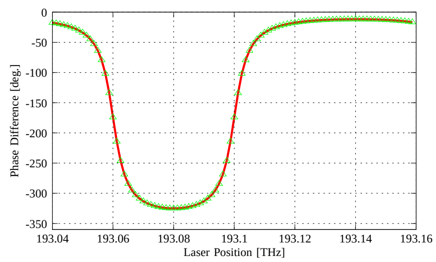

Fig. 3: Induced phase shift for a 40 GHz RF signal in one channel vs laser position in the ring FSR. The triangle symbols indicate the tunable laser discrete steps.

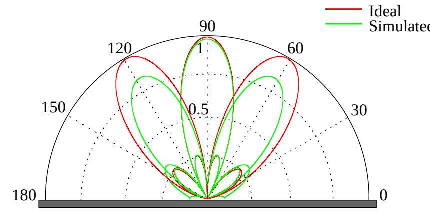

Fig. 4: Radiation diagram vs. Θ [deg.] for a uniform linear 4 element array, for different α values and $d = \lambda/2$

resonators.

The AWG frequency channel spacing must be designed to be equal to an integer multiple of the RR FSR. A critical part of the design is the spectral alignment of the AWG multiplexer and demultiplexer. Either individual thermal tuning or an advanced design with a single 2Nx2 AWG in loopback configuration [9] can solve the problem.

A 4 element beamformer design based in a single ring all-pass section designed in Silicon-On-Insulator is presented. The device simulations are based in a fabricated and characterized RR with waveguide cross-section of 220x500 nm. This waveguide has a group index of 4.25 for TE mode near 1.55 μm wavelength and propagation losses of about 3 dB/cm. The cavity length is set to 711.68μm leading to a FSR close to 99 GHz at the mentioned wavelength. The pair $\Delta\phi_{max}$ and f_{RF} are set to be to 270 degrees and 40 GHz respectively. Fig. 3 shows the induced phase shift between the optical and RF signals while the laser is swept inside an AWG channel. A typical laser step of 10 pm (1.25 GHz) is assumed, though many commercially available tunable have smaller steps. The smaller the laser step, the higher the accuracy of the device beamforming, in terms of both the pointed direction and the available (discrete) set of directions. In Fig. 3 96 positions corresponding to 1.25 GHz steps within a 120 GHz range are shown. Note the aforementioned laser step trade-off, for instance from laser step 16 to 17 there is a phase increment of more than than 30 degrees. The AWGs passbands are designed [10] to have a bandwidth equal to the RR FSR. The full device has been modelled with commercial software [11].

Fig. 4 shows the ideal radiation diagram of the 4 isotropic elements linear array for several progressive phases and the diagram obtained with the simulated device. The main lobe angular mean deviation from theoretical calculations is 0.923 degrees but can easily improved by reducing the tunable laser step. Moreover, the diagram shows a reduced radiation efficiency in the main lobe due to the non-flat RR power transfer function. This could be compensated if the device is implemented in InP technology, with a Semiconductor Optical Amplifier (SOA) placed before each photodetector.

IV. Conclusions

A novel optical beamformer architecture has been presented where the reconfiguration accuracy and time depend on the tunable laser characteristics. The former is easily around 1 pm, therefore providing a nearly continuously tunable device, while the later is in the nanosecond time scale. The device can provide phase shifts up to 360 degrees with a multistage RR design. To optically control the amplitude of the radiant elements, and hence the sidelobe level and null position in the radiation directions, the device can be completely designed in InP with semiconductor optical amplifiers.

References

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nature Photonics*, vol. 1, pp. 319–330, 2007.

[2] D. Adams and C. Madsen, "A novel broadband photonic RF phase shifter," *IEEE Journal of Lightwave Technology*, vol. 26, no. 15, pp. 2712–2717, 2008.

[3] Q. Chang, Q. Li, Z. Zhang, M. Qiu, T. Ye, and Y. Su, "A tunable broadband photonic RF phase shifter based on a silicon microring resonator," *IEEE Photonics Technology Letters*, vol. 21, no. 1, pp. 60–62, 2009.

[4] G. Cocorullo and I. Rendina, "Thermo-optical modulation at 1.5 μm in silicon etalon," *Electronics Letters*, vol. 28, no. 1, pp. 83–85, 1992.

[5] V. Almeida and M. Lipson, "Optical bistability on a silicon chip," *Opt. Letters*, vol. 29, no. 20, pp. 2387–2389, 2004.

[6] G. Alibert, F. Delorme, P. Boulet, J. Landreau, and H. Nakajima, "Subnanosecond tunable laser using a single electroabsorption tuning super structure grating," *IEEE Photonics Technology Letters*, vol. 9, no. 7, pp. 895–897, 1997.

[7] C. K. Madsen and G. Lenz, "Optical all-pass filters for phase response design with applications for dispersion compensation," *IEEE Photonics Technology Letters*, vol. 10, pp. 994–996, July 1998.

[8] J. E. Heebner, R. W. Boyd, and Q.-H. Park, "Scissor solitons and other novel propagation effects in microresonator-modified waveguides," *J. Opt. Soc. Am. B*, vol. 19, no. 4, pp. 722–731, 2002.

[9] P. Munoz, J. D. Domenech, M. Manzanedo, J. Den Besten, E. Verdumen, and J. Capmany, "Design of arrayed waveguide sagnac interferometers for OTDM-WDM optical networks," *5th Reunión Española de Optoelectrónica*, 2007.

[10] P. Munoz, D. Pastor, and J. Capmany, "Modeling and design of arrayed waveguide gratings," *IEEE Journal of Lightwave Technology*, vol. 20, no. 4, pp. 661–674, 2002.

[11] VPItransmissionMaker/VPIcomponentMaker Version 8.0, VPIsystems Inc., www.vpiphotonics.com.