

# A Si<sub>3</sub>N<sub>4</sub> Optical Ring Resonator True time delay for Optically-assisted Satellite Radio Beamforming

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*We present the design, fabrication and characterization of a Si<sub>3</sub>N<sub>4</sub> optical ring resonator true time delay to be used in optically-assisted radio beamforming. A race track shaped ring resonator with a free spectral range of 0.21 nm was designed, fabricated and tested. Experimental characterization verified continuous thermal tunability of resonance wavelength of 0.1nm/10 V. The continuous tunability of the ORR for under-coupling, critical-coupling and over-coupling conditions was measured. This full tunability allows dynamic configurability of the delay for applications in satellite radio beamforming.*

## Introduction

Radio beamforming is an essential in meeting the ever growing bandwidth demand of wireless communication users. Traditional implementation of wide band beamformer faces challenges due to bandwidth and size limitations of electrical phase shifters [1]. True Time Delay (TTD) devices solve this problem, by providing a broadband phase shift for wideband signals via a time delay. However, TTD devices based on bulky optics have their own limitations due to large size and optical losses; making it impractical for deployment in a beamforming system. Photonic integrated TTD is the ultimate solution in meeting the challenges of a wide band radio beamformer [1-3]. In this regard optical ring resonators (ORR) are popularly implemented as TTD devices since it is possible to fine tune the generated time delay, allowing continuous beam-steering. This feature is very important in radar and satellite communication, where continuous beam-steering is required to trace a far field transceiver [3].

In this paper, we report the design, fabrication and characterization of an ORR with Free Spectral Range (FSR) of 0.21nm designed for application in radio-satellite beamforming. The measured power spectral profiles verified the full tunability of the ORR with an over-coupling, under-coupling and critical-coupling conditions. Wavelength tunability was verified; resulting in 0.1 nm shift in the resonance wavelength per 10 V of applied voltage.

## Operational Principles of ORR

Here we describe the operational principle of a 2-port ORR which typically consists of a feedback path (the ring) and a 2×2 coupler. A light injected into the input waveguide couples to the ring; all wavelengths fulfilling resonance condition propagate multiple round trips before coupling out into the output waveguide. Fig. 1 shows the schematic representation of an ORR. For an ORR, with power transmission coefficient of  $\gamma$ , coupling coefficient  $\kappa$  and frequency normalized with respect to FSR,  $\Omega$ , applied additional phase shift  $\phi$ , the power spectral response in dB of an ORR is given by:

$$|H(\Omega)|^2 = 10 \log_{10} \left[ \frac{1 - \kappa + \gamma^2 - 2\gamma\sqrt{1 - \kappa} \cos(\Omega + \phi)}{1 + \gamma^2(1 - \kappa) - 2\gamma\sqrt{1 - \kappa} \cos(\Omega + \phi)} \right] \quad \dots \quad (I)$$

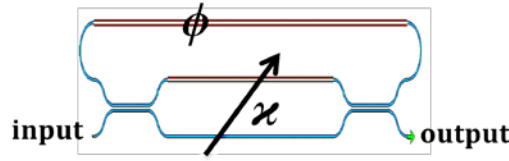


Fig. 1 Schematic diagram of an optical ring resonator

When the coupler is designed to be thermo-optically tunable, continuous delay can be generated. A tunable optical coupler is implemented by using a Mach-Zehnder interferometer (MZI) with thermo-optic phase shifters (heaters) on the upper arm. A control voltage applied on one arm of the MZI changes the refractive index of the waveguide, thus changing the phase difference between the arms; thereby continuously tuning the power coupling coefficient  $\kappa$ . As a result, the group delay profile of the ORR is tuned. The group delay profile is given by eqn (II).

$$T(\Omega) = \frac{\gamma\sqrt{1 - \kappa} \cos(\Omega + \phi) - \gamma^2\sqrt{1 - \kappa}}{1 - 2\gamma\sqrt{1 - \kappa} \cos(\Omega + \phi) + \gamma^2\sqrt{1 - \kappa}} + \frac{\gamma^2 - \gamma\sqrt{1 - \kappa} \cos(\Omega + \phi)}{1 - \kappa - 2\gamma\sqrt{1 - \kappa} \cos(\Omega + \phi) + \gamma^2} \quad \dots \quad (II)$$

The group delay profile of an ORR is bell-shaped where the largest delay is generated at resonant wavelengths. Additional phase shift  $\phi$  allows adjusting the resonance wavelength of the ORR. Fig. 2(a) and Fig. 2 (b) are theoretical plots showing the tuning principle of the power and delay profile of the ORR for different coupling coefficients  $\kappa$ . For high power coupling coefficient (over-coupling condition, greater than 0.3 in this case), the resonance of light inside the ring is limited to a few round trips, resulting in smaller losses at resonance wavelength. For lower coupling coefficients, which happen under-coupling conditions (less than 0.3 in this case), however, light stays longer at the resonance wavelengths leading to higher losses at resonance wavelengths. For critical-coupling conditions, the light stays the longest at resonance thus producing largest optical losses. In this case, the coupling loss is equal to the loss per round trip of the ORR, resulting in the largest optical delay of the ORR. The critical coupling condition,

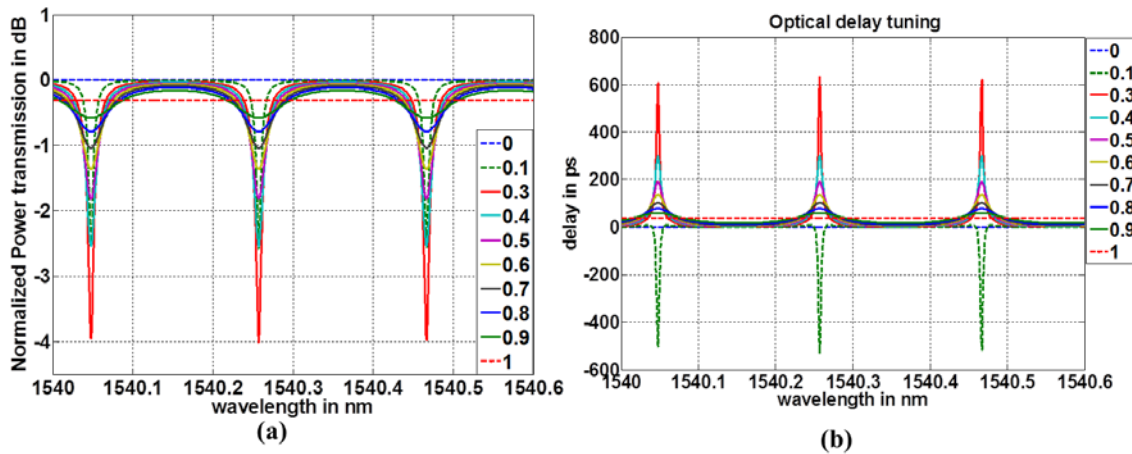


Fig. 2(a) power response of the ORR under different coupling condition, Fig.2 (b) group delay profile of the ORR for different coupling conditions

$\kappa_c$ , is given by:

$$\kappa_c = 1 - \gamma^2 \quad \dots \text{(III)}$$

From Fig. 2(b) critical coupling condition happens at the coupling coefficient of 0.3. A positive delay profile is generated during over-coupling condition. The highest positive group delay is measured during critical coupling condition. A negative group delay profile is generated for under-coupling conditions.

## Design and Fabrication of the ORR

The microscopic representation of the designed ORR is shown in Fig. 3 (a). It consists of a tunable coupler realized by a Mach-Zehnder Interferometer (MZI). The MZI is made of two 3dB directional couplers, with a thermo-optic phase shifter in the middle. The phase shifter is 2000  $\mu\text{m}$ , and is used to provide full tunability of the coupling coefficient from 0 to 1. A bending radius limitation of 125  $\mu\text{m}$  was followed to avoid optical losses related with bending. A double stripe waveguide technology Triplex<sup>TM</sup> is used in the fabrication process. In this technology, a  $\text{SiO}_2$  sandwiched between two  $\text{Si}_3\text{N}_4$  passes through a CMOS-compatible low-pressure chemical vapour disposition process (LPCVD) generating a typical surface roughness less than 0.04 nm. The platform has moderate index contrast and low waveguide loss less than 0.5dB/cm. The detailed fabrication process of a double stripe  $\text{Si}_3\text{N}_4$  waveguide is found in [4]. The phase shifters are fabricated by depositing a layer of chromium on the top of the optical waveguides. The heaters can be tuned with a temperature resolution of 0.01°C enabling fine tuning of the generated optical delays. By keeping a space of 250 $\mu\text{m}$  between any two thermo-optic phase shifters, any thermal cross talk is avoided. DC contact pads are connected to the heaters via electrical leads made of chromium and gold. Spot-size converters are used at the two ends of the chip to efficiently couple TE mode with a single mode fiber (SMF 28) for target coupling losses of less than 1dB per facet.

## Measurement Results

Fig. 3(a) shows the fiber-to-chip coupling setup used to characterize the ORR. The thermo-optic tuning is facilitated by DC probes which supply DC voltages to the heaters. A fiber-to-fiber coupling loss of 9dB (including 2 dB polarization controller loss) was measured. Fig. 3(b) shows the microscopic photograph of the ORR. By tuning the voltage Heater-1, it is possible to shift the resonance wavelength. A 0.1 nm shift in the spectral response of the ORR was obtained per 10 V variation of voltage applied on Heater-1 as can be seen in Fig. 3(c). Fig. 3 (d) and Fig. 3(e) show the tuning of the ORR response by changing the applied voltage on Heater-2, where the coupling coefficient change produces the change in the spectral shape of the ORR response. It is possible to observe the over-coupling, the critical-coupling and under-coupling conditions. When the applied voltage is tuned from 9.6 V to 13.2 V (over-coupling condition), the loss at the resonance wavelength changes from 1dB to 6 dB. The critical-coupling condition is measured at voltage value of 14 V applied on Heater-2, with resonant loss reaching up to 8.5 dB. By further increasing the applied voltage, under-coupling condition is observed for 15-16 Volts as shown in Fig. 4(e). At applied voltage of 17.5 V, no light is coupled to the ring, rather is transmitted to the output waveguide. In this situation the ORR serves as an optical waveguide. From experimental results, it

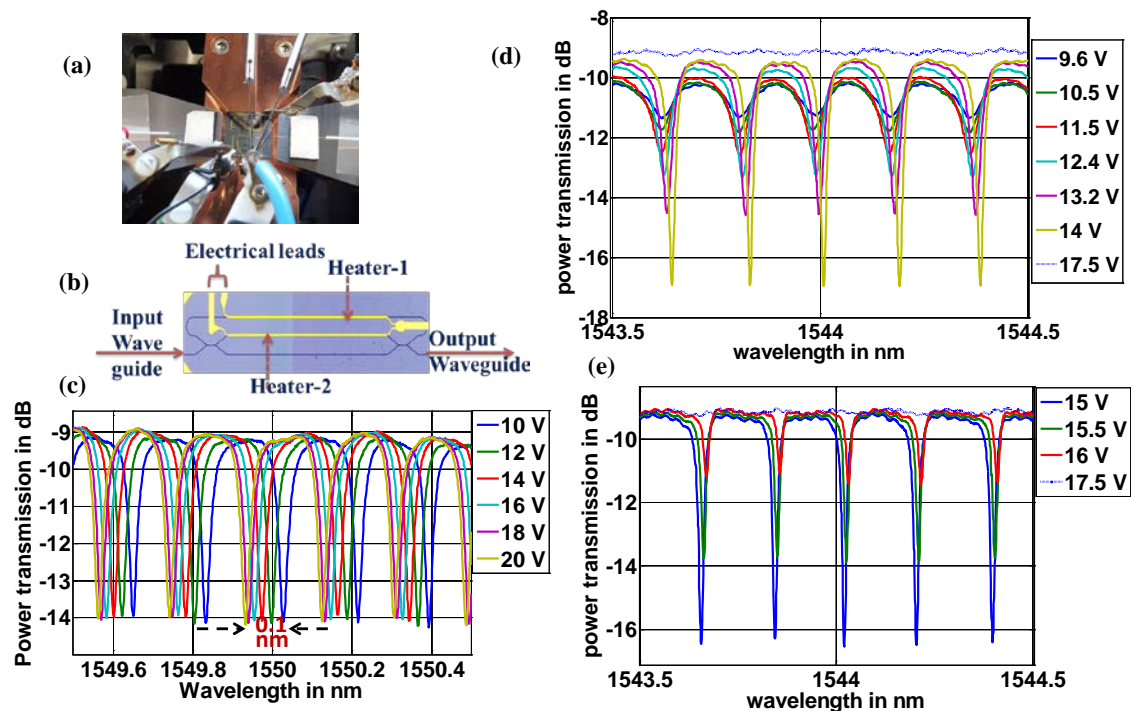


Fig. 3(a) The optical chip measurement set up (b) Microscopic photograph of the measured ORR (c) Resonant detuning, 0.1 nm/10 V shift, (d) Power response of the ORR in over and critical coupling conditions (e) Power response of the ORR in under coupling conditions

is verified that the fabricated ORR is fully tunable, which indicates its capability to be deployed as a TTD in radio beamformer link.

## Conclusions

We designed, fabricated and tested an optical ring resonator for application as true time delay device for radio beamforming. Dynamic configuration of the device was characterized via thermo-optic tuning.

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