Reconfigurable Double-Injection Ring Resonator for Integrated Microwave Photonic Signal Processing

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***Abstract*—Integrated microwave photonic (MWP) signal processor relies on the integration of multiple optical circuits, advanced functionalities, and high-performance for radio frequency (RF) applications. In this paper, we experimentally investigated a new kind of an on-chip MWP signal processor in silicon nitride, containing of a Modulation Transformer (MT) and a Double-Injection Ring Resonator (DIRR). This optical circuit enables the synthesis of reconfigurable spectral shaping for advanced functionality unmatched by conventional MWP circuits.**

Keywords—silicon nitride, integrated, microwave, photonics, ring resonator, signal processing.

I. Introduction

Microwave photonic (MWP) signal processor with integrated circuits, advanced functionality, and exceptional performance play an important role to shape any optical modulation spectrum for real radio frequency (RF) or microwave systems applications [1, 2]. Such device requires ultra-versatile optical circuits to independently manipulate phase and amplitude relation of the optical carrier and the sidebands.

Recently, we identified that a promising route to achieve the best combination of integration, advanced functionality, and high-performance is by simultaneously program the modulation spectrum through a versatile modulation transformer (MT) consisting of a spectral de-interleaver with three ring resonators (RRs), a tunable attenuator, a phase shifter, and a combiner as shown in Fig. 1(a) [3, 4]. Meanwhile, the type of functionality that can be synthesized in an existing circuit is controlled by the combination of modulation with phase and amplitude manipulation derived from an optical signal processor such as ring resonator (RR). Recently, a demonstration of an ultra-versatile optical processor based on a double-injection ring resonator (DIRR) synthesizing various unique functions were reported [5]. However, the report only focuses on the investigations of various shaped transmission responses of such a resonator [6]. For MWP, versatility in shaping both the amplitude and the phase response of this resonator needs to be investigated.

In this paper, we investigate experimentally the combination of a MT and a DIRR integrated in a single silicon nitride (Si_3N_4) photonic chip as shown in Fig. 1(c). The MT is used to synthesize various optical modulation spectrum, while the DIRR is used to synthesize variety of optical responses from a single output unmatched by conventional all-pass ring resonator or add-drop ring resonator. Here, we investigated not only the transmission responses in radio frequency (RF) domain, but also the phase responses of DIRR. This device is a powerful tool for opening avenues to advanced functionalities and high-performance MWP systems.

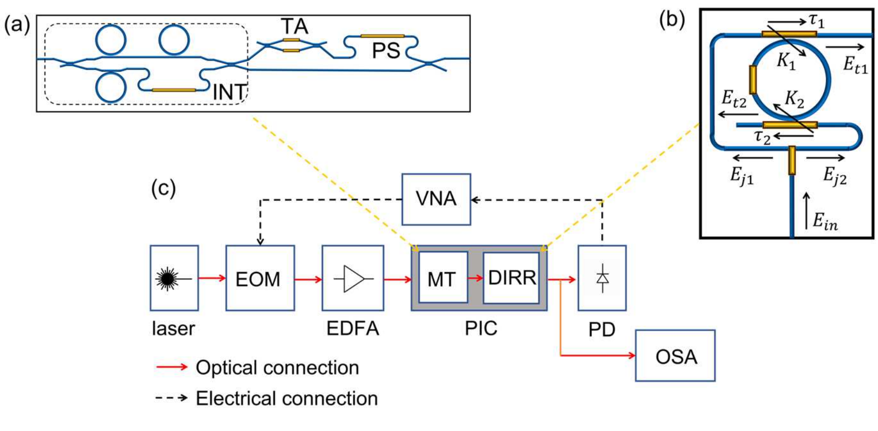

Fig. 1. Diagram and schematic of (a) Modulation transformer (MT), (b) Double-injection ring resonator (DIRR), and (c) Diagram of experiments setup used for investigation; INT: interleaver, TA: tunable attenuator, PS: phase shifter, EOM: electro-optic modulator, EDFA: Erbium-doped Fiber Amplifier, PIC: photonic integrated circuit, PD: photodetector, VNA: vector network analyzer, OSA: optical spectrum analyzer.

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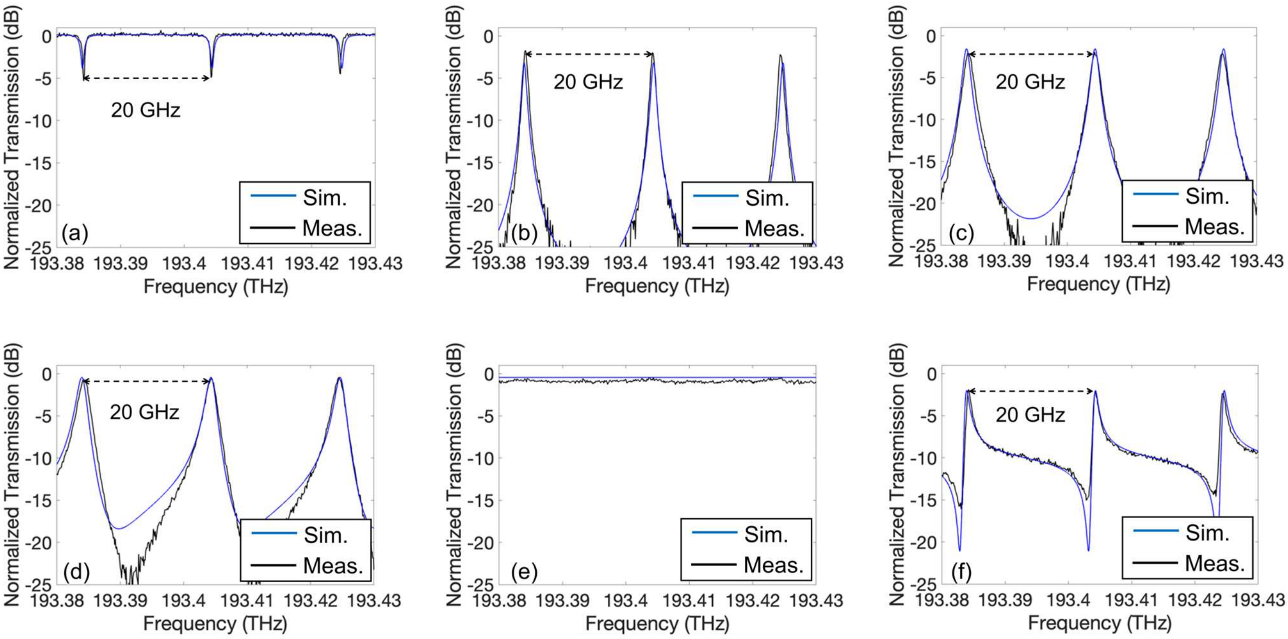

Fig. 2. The variety of simulation and experimental results of the Double-Injection Ring Resonator (DIRR) measured in the optical domain using an optical spectrum analyzer. (a) notch filter, (b) bandpass filter, (c) triangular response, (d) sawtooth response, (e) all-pass response, and (f) Fano-like response; Sim.: simulations, Meas.: measurements.

II. Operational Principles

A. Modulation Transformer

In a MWP systems, an optical modulation spectrum plays an important role. It virtually dictates the losses, signal-to-noise ratio (SNR), and linearity of the systems, and critically impacts of how well one can map tailored optical functionalities to the RF domain [4]. Previous researches have showed that a precise control of phases and amplitudes of an optical modulation spectrum can open to a new MWP signal processing functions, including advanced RF photonic filters [7, 8]. However, such foundational functionalities are currently unrealizable with any type of existing optical modulators, due to the interrelated phases and amplitudes of optical carrier and sidebands.

Recently, a device named modulation transformer [3] was proposed to shape and synthesize arbitrary MWP spectra. This device takes an input of any modulation spectrum and synthesize different output modulation spectrum with entirely independent phases and amplitudes relation of optical carrier and sidebands. We implement the MT as two outputs spectral de-interleaver followed by a tunable attenuator and a phase shifter at one of the output while the complementary output is connected to the DIRR. Here, the spectral de-interleaver is a “box shaped” filter with 20 dB rejection, 4 GHz of band-edges between two output ports, and 80 GHz of bandwidth. In our experiments, we configure the MT as a single sideband with carrier re-insertion filter.

B. Double-Injection Ring Resonator

In the recent publication [5], a response shaping of RR with double-injection (DI) is presented. It was aimed to provide multiple unique responses in a RR based optical circuit from single output. The underlying idea of this circuit is to inject two, mutually coherent, optical signals of the same wavelength into a single add-drop ring resonator from single input. Later, we further investigate the variety of phase of each unique response synthesized by DIRR, which is a key parameter for MWP signal processing.

Figure 1(b) shows the schematic of DIRR circuit. Multiple electro-optic tuning elements are attached in the circuit to split the input optical signal and tune the coupling coefficient and central frequency of the ring responses. By precisely controlling these tuning elements, we can synthesize variety of responses from single output. Mathematically, the model describing the transmitted electric field dependence on the wavelength of DIRR is given by [5],

$$E_{t1}(\lambda) = \frac{(\tau_1 - \tau_2{}^*\alpha e^{-j\theta})}{1-\tau_1\tau_2{}^*\alpha e^{-j\theta}}\left|E_{j1}(\lambda)\right|e^{-j\phi_{j1}} - \frac{K_1K_2{}^*\sqrt{\alpha}e^{-j\theta}}{1-\tau_1\tau_2{}^*\alpha e^{-j\theta}}\left|E_{j2}(\lambda)\right|e^{-j\phi_{j2}} \quad (1)$$

where $\tau = |\tau|e^{-j\varphi_\tau}$ is the transmission of the directional coupler, $K = |K|e^{-j\varphi_K}$ is the coupling coefficients of the directional couplers, α is the loss coefficient of the ring, E_j is the injected fields, and ϕ_j is the injected fields phases. θ is the phase accumulated by the light traversing the ring at steady state that described as,

$$\theta(\lambda) = \frac{2\pi}{\lambda} n_{eff}(\lambda) L_{ring} \quad (2)$$

with λ being the wavelength, L_{ring} the perimeter of the ring, and n_{eff} the effective index of the propagating mode.

III. Experiments

The experiments setup for our investigations is shown in Fig. 1(c). During the experiments, an optical carrier from low relative-intensity noise (RIN) laser (Pure Photonics PPCL550) with RIN of -155 dB/Hz and wavelength set at 1550 nm is modulated using a dual parallel Mach Zehnder modulator (DPMZM, Thorlabs 25 GHz) with bias point set to synthesize single sideband (SSB) modulation. The DPMZM is driven by

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RF signal from a vector network analyzer (VNA, Keysight P5007A, 44 GHz). The output of the DPMZM then sent to a low noise erbium-doped fiber amplifier (EDFA, Amonics) before being injected into a programmable silicon nitride photonic chip (LioniX International BV) fabricated using low-loss TriPleX (Si_3N_4/SiO_2) technology [9] with propagation loss of the optical waveguide at 0.1 dB/cm. The free spectral ranges (FSRs) of the spectral de-interleaver and the DIRR are 160 GHz and 20 GHz, respectively. The coupling coefficient and resonance frequency are tuneable through thermo-optic tuning, controlled using multichannel voltage supply with software reconfiguration. The chip temperature is stabilized by a thermoelectric-cooler (TEC) controller. The processed optical signal is sent to a photodetector (APIC 40 GHz) and the converted RF signal is measured with a VNA.

A. *Transmission responses*

First, we investigate the transmission of the DIRR. This approach is important to observe the wide variety of unique amplitude responses of DIRR that overcome the responses of a more traditional all-pass ring resonator or add-drop ring resonator. In these investigations, we use a broadband optical source, super-luminescent diode (SLD, Thorlabs) that is being injected to DIRR and observe the transmission in optical domain using a high-resolution optical spectrum analyzer (Waveanalyzer, Finisar). Then, by precisely tuning nine different heaters in the DIRR, we synthesize six different responses from single output. Here, we program the ring to be in different state of the ring, such as the state of an all-pass ring, an add-drop ring, and between the all-pass and the add-drop ring.

The simulated and measured amplitude responses of DIRR from single output are shown in Fig. 2(a) – (f). First is a notch response as shown in Fig. 2(a). The key element of synthesizing this response is in the tunable coupler at the input of DIRR. By controlling the ratio of $E_{j1}(\lambda)$ and $E_{j2}(\lambda)$ in Fig. 1(b) until $E_{j1}(\lambda) >> E_{j2}(\lambda)$, the DIRR can be programmed as an all-pass ring and synthesize a notch response. Then, if we switch the ratio of $E_{j1}(\lambda)$ and $E_{j2}(\lambda)$ to $E_{j1}(\lambda) << E_{j2}(\lambda)$, the DIRR can be configured as an add-drop ring and synthesize a bandpass response as shown in Fig. 2(b). Here, if we further control the injected fields phase (ϕ_j), we can synthesize four additional unique responses from the ring that cannot be matched by conventional all-pass ring resonator or add-drop ring resonator, such as triangular response as shown in Fig. 2(c), sawtooth response as shown in Fig. 2(d), all-pass response as shown in Fig. 2(e), and a Fano-like response as shown in Fig. 2(f). These responses have shown the variety of shaped responses synthesized by DIRR in a single input – single output transmission.

B. *Phase responses*

We further investigate the variety of phase responses from each synthesized transmission explained in previous section. The phase response has an important role as transmission response in MWP system for signal manipulations [10]. Here, we switch the experiments domain from optical to RF with setup shown in Fig. 1(c). In particular, we use the MT for optical re-insertion technique to form a single sideband with carrier spectrum for accurately determining the amplitude and phase responses of narrowband bandpass filters. The diagram of the DIRR response investigation in RF domain with embedded MT is shown in Fig. 3.

A single sideband modulation (Fig. 3(a)) is sent to spectral de-interleaver with two outputs (Bar and Cross, Fig. 3(b)). These outputs spectrally isolate the optical carrier from the sideband. The Bar output contains the optical carrier (Fig. 3(c)) is sent through a tunable attenuator and a phase shifter. Meanwhile, the Cross port contains the sideband (Fig. 3(d)) is sent to the DIRR to be processed with a response explained in previous section (Fig. 3(e)). Last, a combiner is re-inserted the optical carrier to the processed sideband and sent the combined spectrum to a photodetector to synthesize phase and amplitude response in RF domain as shown in Fig. 3(f).

Figure 4(a) – (f) show the synthesized phase and amplitude responses of DIRR from single output with the inset figures show its corresponding figures in optical domain shown in Fig. 2. Here, the transmission (τ) and the coupling coefficients

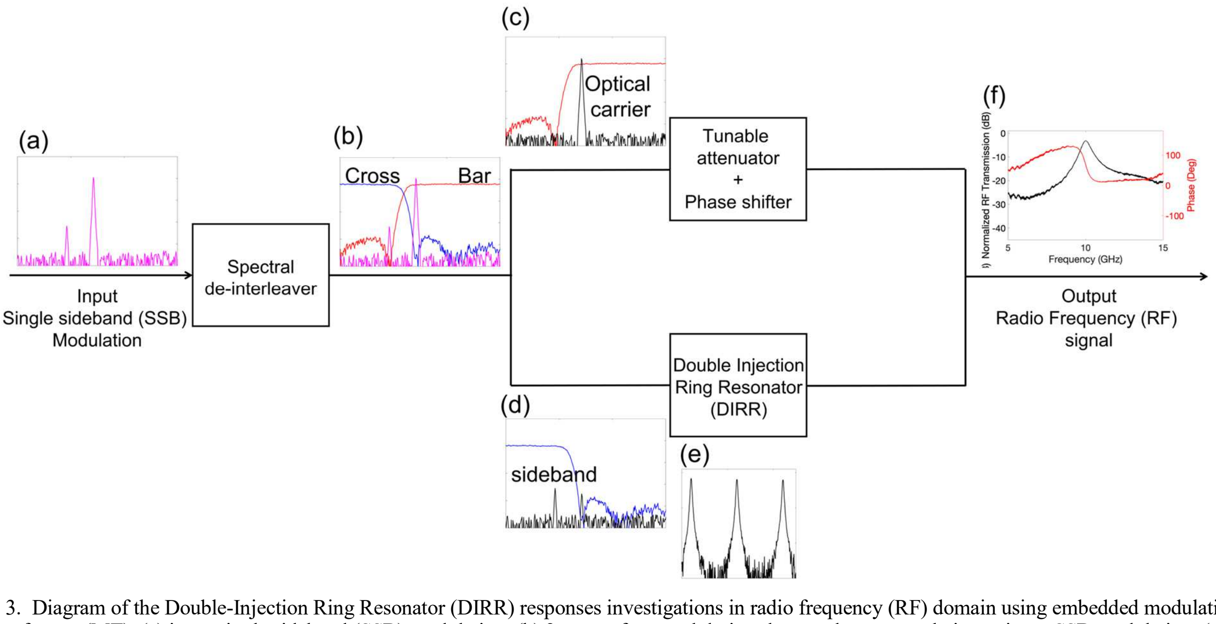

Fig. 3. Diagram of the Double-Injection Ring Resonator (DIRR) responses investigations in radio frequency (RF) domain using embedded modulation transformer (MT). (a) input single sideband (SSB) modulation, (b) 2 ports of spectral de-interleaver placement relative to input SSB modulation, (c) output of Bar port containing optical carrier, (d) output of Cross port containing sideband, (e) DIRR's response, and (f) output RF signal

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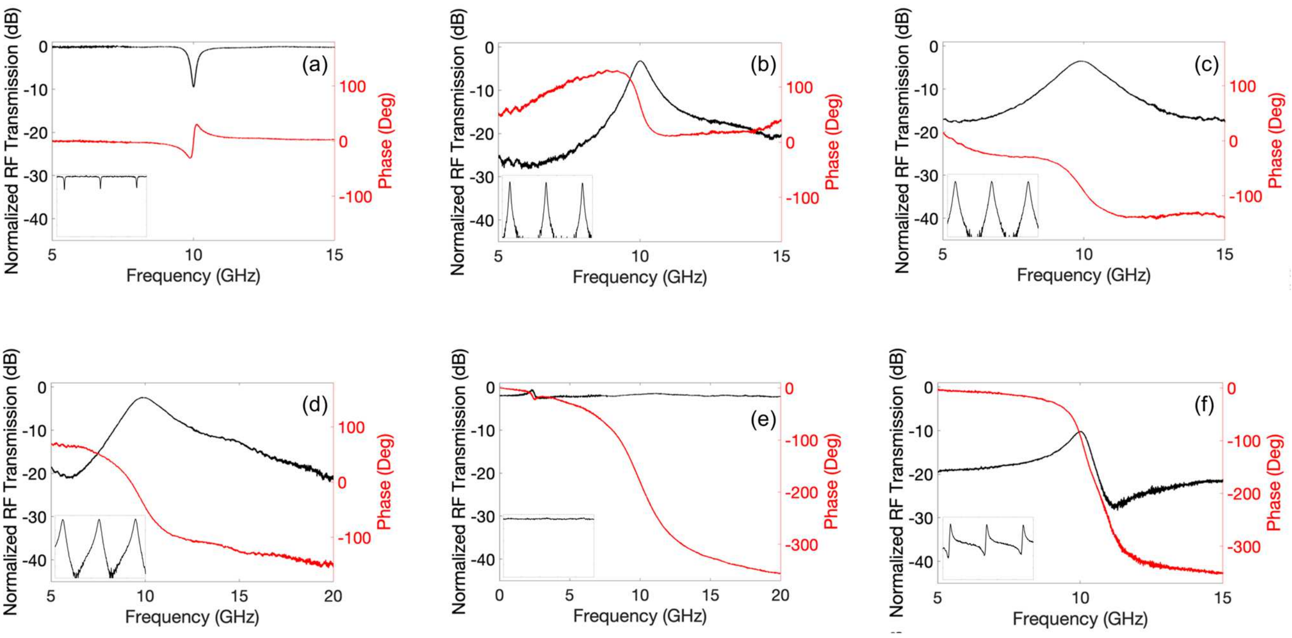

Fig. 4. The variety of experimental results of the Double-Injection Ring Resonator (DIRR) in radio frequency (RF) domain with both amplitudes and phases (inset: corresponding optical responses). (a) notch, (b) bandpass, (c) triangular, (d) sawtooth, (e) all-pass, and (f) Fano-like response.

(K) of the directional couplers in the ring play equally important role for phase investigations. By controlling the value of τ and K, we can synthesize different phase responses from the ring, such as under-coupling notch response with 0-degree phase response at the resonance as shown in Fig. 4(a). Then, the same approach of phase investigation can be applied to synthesize bandpass phase and amplitude response as shown in Fig. 4(b) when we precisely control E_j, ϕ_j, τ, and K. Last, four different phases and amplitudes of unique responses are investigated, such as triangular as shown in Fig. 4(c), sawtooth as shown in Fig. 4(d), all-pass as shown in Fig. 4(e), and a Fano-like response, showing a combination of stop-and-pass bands as shown in Fig. 4(f). These phase and amplitude responses have shown that we can use the circuit to perform multiple advanced functionalities for MWP systems.

A potential real application of such circuit is not limited to RF filters, but also an RF phase shifter. It applies when the DIRR set to synthesize a relatively flat all-pass amplitude response with 2π-phase shift for 20 GHz of bandwidth as shown in Fig. 4(e). Moreover, with the combination of a MT and a DIRR integrated in a single photonic chip, we can create an RF phase shifter with high performance.

IV. Conclusion

We investigated experimentally the combination of a MT and a DIRR in a single silicon nitride (Si_3N_4) photonic chip. The DIRR can be reconfigured and synthesize variety of unique phase and amplitude responses for multiple advanced functionalities in a MWP system such as RF filters or RF phase shifter.

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