Design of Nonlinear Optical Ring Resonators

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Abstract: We present a design methodology of nonlinear microring resonators based on iterations of matrix analysis. This new method is time/memory efficient and scalable, and can be applied to other nonlinear devices.
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1. Introduction

Nonlinear optical devices are needed for optical memory, switching, and logic functions in next-generation photonic integrated circuits [1]. Materials with strong nonlinear optical properties, such as AlGaAs, are the clear choices in the past [2]. Thanks to silicon's third-order nonlinear effects and tight mode confinement in silicon photonic wires, now silcion is also considered a potential technology platform for nonlinear photonics [3]. Resonators such as microrings can further enhance light confinement, increase optical intensity, and hence generate larger optical nonlinear effects. Ring-based silicon nonlinear optical devices and circuits have been demonstrated, such as bistability [4] and optical neurons [5]. This paper presents a new design methodology for nonlinear microring resonators with low computational cost.

2. Design Methodology

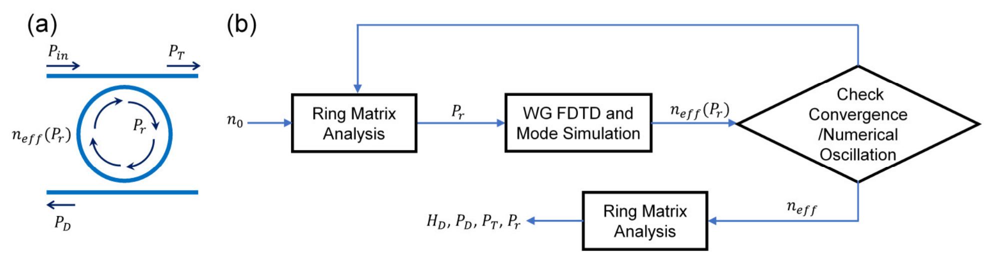

Fig. 1. (a) A nonlinear microring resonator. P_{in}, P_T and P_D are optical power at the input, through, and drop ports; P_r is that inside the ring. (b) Proposed nonlinear micoring resonator design flow. n_0 is the effective refractive index of the waveguide in the linear region, and $n_{eff}(P_r)$ is that in the nonlinear region corresponding to an optical power P_r.

The analysis of a nonlinear optical device typically requires modeling the device at all optical power levels for all wavelengths involved using FDTD simulations. To do this for any device with a reasonably complex structure such as a ring, however, is very challenging, since the required computation resources (memory and simulation time) would be overwhelming. To overcome this computing barrier, we propose a new method based on iteratiations of *linear* analysis of the device to search for the effective index and corresponding internal optical power.

Fig. 1 shows the proposed design flow of a nonlinear ring resonator. First, the optical waveguide for the ring is simulated by FDTD device simulations with different optical power to generate a table of effective index versus optical power. Then at each wavelength, we run iterations of linear anaysis, in this case matrix analysis, for the ring. We initially set the effective index to its value in the linear region. Using matrix analysis of the ring [6], we calculate the optical power inside the ring (P_r), and look up the new effective index from the earlier table. This iteration is repreated until the results converges. When the optical power is high enough, numerical oscillation may occur in the iterations at certain wavelengths. In this case, we use the squeeze method by taking the mean value of the maximum and minimum values of the oscillation as our new effective index, and continue the iteration. After the effective index is found, the matrix analysis is run one last time to calculate the output power at the drop and through ports as well as the transfer functions.

Note that computation intensive device simulations of the waveguide are only run once for the specific technology, and the generated table of waveguide effective index vs optical power can be used used for different ring designs and even other nonlinear devices.

3. Design Example

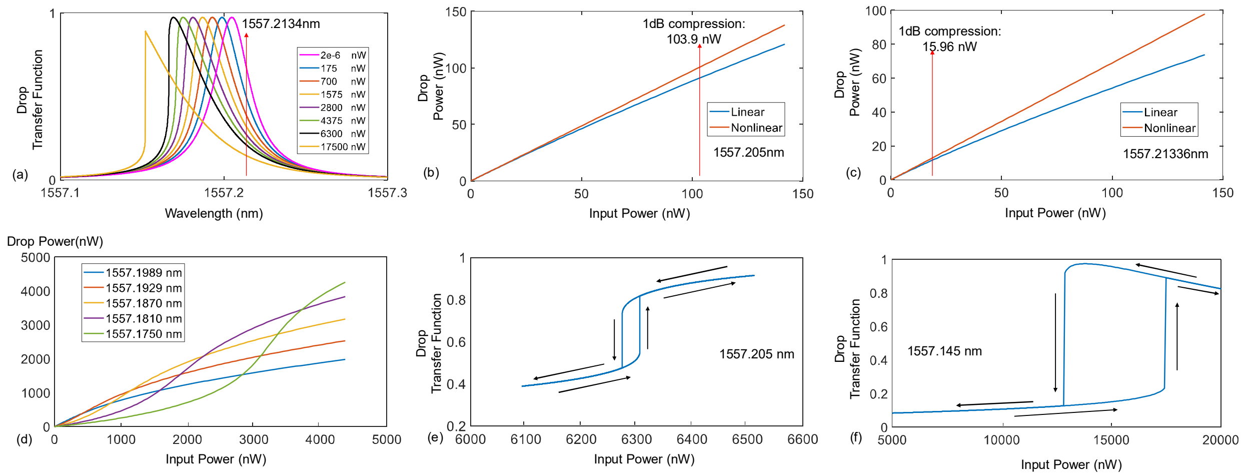

Fig. 2. (a) Spectra of the ring resonator at different *input* optical power levels. The purple curve corresponds to the spetrum when the ring operates in the linear region. Drop port power vs. input power (b) when operating at the resonance wavelength in the linear region, (c) with lowest 1 dB compression point, and (d) at different operation wavelengths. (e) Bistability effect at 1557.205 nm. (f) Bistability effect at 1557.145 nm.

To demonstrate the proposed design method, we design a lithium niobate (LN) nonlinear microring resonator with double coupling bus waveguides. The device is built in a LN-on-SOI technology [7] with a 2-μm SiO_2 buried oxide layer and 10-Ω-cm silicon substrate. The ring has a 50-μm radius with a quality factor of 5.9×10^4. The results using the proposed method is shown in Fig. 2.

From the spectra of the drop port transfer function in Fig. 2-a, we can see that the resonance moves to shorter wavelength and the spectrum becomes asymmetric as the input power increases due to more pronounced nonliearity. When the input power is high enough, a jump in the transfer function shows up at resonance.

To quantify the nonlinear characteristics of the transfer function at the operation wavelength, we plot the drop port output power vs. input power in Fig. 2-bc. For comparison, the extrapolated linear transfer function is also plotted (the red curve). A qualitative measure of nonlinearity, input 1-dB compression point, can be found from these two curves. The input 1-dB compression point changes with the operation wavelength. At the resonance wavelength when the ring operates in the linear region (1557.205 nm), it is located at 103.9 nW (Fig. 2-b). At 1557.2134 nm, as marked by the red arraow in Fig. 2-a, the gap between the linear and nonlinear spectra is maximized, and the lowest 1-dB compress point is achieved at 16 nW, as shown in Fig. 2-c.

If the operation wavelength is shorter than the linear resonance wavelength, the linear and weakly nonlinear spectra curves have oppsite slopes from those strongly nonlinear ones (Fig. 2-a). As the input power and hence nonlinearity increases, therefore, the drop port power increases at varying rates, generating an S-shape nonlinear transfer function, as shown in Fig. 2-d. The S-shape becomes more pronounced as the operation wavelength moves further away from the linear resonance wavelength.

We can also observer bistability behavior if we do both the ramp-up and ramp-down on the input power during the search iterations in the design flow, i.e., using the effective index as the initial value for the next step in power, as shown in Fig. 2-ef. The bistability effect is more pronounced when the operation wavelength is shorter, and correspondingly the input power required to excite the bistability is higher.

References

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