Dynamic models of microring resonators

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***Abstract*—Quasi-static microring models assume the intracavity optical field adiabatically follows the modulated parameter(s). A non-quasi-static model shows the modulation of the microring coupling coefficient breaks the traditional trade-offs between the modulation rate and resonator linewidth.**

***Keywords*—optical resonators, microrings, modulators, integrated optical devices**

I. Introduction

Microring resonators have attracted significant interest as active and passive integrated photonic components, including optical filters, wavelength multiplexers/demultiplexers, modulators, and lasers. Fully three-dimensional, time-dependent, numerical simulations of microring devices are often intractable. Fortuitously, due to the simple modal characteristics of microring resonators compared to other types of microcavities (e.g., photonic crystals or microdisks), their analysis can often be simplified. At low optical intensities, below the onset of nonlinearities, the optical transmission of microring devices are completely described by the round-trip phase-shift, losses, and coupling coefficients. The round-trip phase sets the resonance wavelengths, and the losses and coupling coefficients determine the cavity dissipation.

For situations where the microring properties are static (e.g., in filters), microrings can be modelled with transfer or scattering matrices in the frequency domain [1-3] or harmonic oscillator equations in the time domain [4]. These approaches are equivalent in the weak coupling limit [5], and have produced results that generally agree well with experiments. The dynamics of microrings, and microcavities in general, are important for the design of active devices such as modulators and lasers. In this situation, some properties of the microring, such as its round-trip phase, loss, and coupling coefficients, are modulated and become arbitrary functions of time.

In this talk, I will describe the analytical approaches to model the dynamic properties of the microrings with an emphasis on modulator applications. The analyses illustrate the trade-offs in the modulation rates, chirp, and efficiency of resonant modulators. I will describe how this trade-off can be circumvented via "coupling modulation," where the output coupling of the microring is modulated rather than its intracavity phase-shift or loss.

II. Quasi-Static vs. Non-Quasi-Static

The unique property of resonators is the coherent, multi-round-trip constructive or destructive interference that occurs at specific wavelengths. As the constructive interference is set up, optical energy is built up in the resonator; and during the process of destructive interference, energy is discharged from the resonator. The time required for the interference to be set up is dictated by the photon cavity lifetime, which is inversely proportional to the linewidth.

Based on the photon cavity lifetime, we define two regimes of microring dynamics: "quasi-static" and "non-quasi-static" [6]. In the quasi-static regime, the variations in the microring properties occur on timescales much longer than the photon cavity lifetime, whereas in the non-quasi-static regime, the variations occur on timescales comparable to or shorter than the photon cavity lifetime.

Quasi-static dynamics are well modeled using the steady-state transfer functions of the resonator device. One simply introduces time-dependences into the parameters of the steady-state transfer functions. Thus, the quasi-static description assumes the optical fields adiabatically follow the modulated parameters. Such descriptions have been common in the technical community and are often used to explain microring modulators [e.g., 7-9]. Since most microrings have linewidths around several GHz, the quasi-static model holds for modulation occurring at 10 to 10^2 picosecond time scales.

The non-quasi-static regime requires a fully dynamic description in space and time. In [10], we presented such a model for a single bus-coupled microring modulator. The time-dependent intracavity field leads to a recursive expression for the output transmission, such that the present value of the transmission depends on its past value. The result should not be surprising, since a resonator has "memory" due to the storage of the circulating light. With certain simplifications, the recursive relationships can have exact analytical solutions [10]. Otherwise, they can be solved numerically.

III. Coupling Modulation

From the model in [10], we found that the modulation of the microring coupling coefficient, which we term "coupling modulation," leads to fundamentally different operation characteristics compared to the modulation of the refractive index or loss in the resonator, which we term "intracavity modulation." In particular, the modulation rate of coupling modulation is not bound by the cavity linewidth.

This difference can be shown mathematically [10, 11], but it can also be understood intuitively. In intracavity modulation, each modulation cycle requires the nearly complete constructive and destructive interference of the intracavity

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field, which takes a time on the order of the photon cavity lifetime to finish. In contrast, in coupling modulation, the coupler provides an instantaneous gating of the intracavity field as it exits the resonator. The amplitude of the intracavity field is only minimally perturbed if the modulation amplitude is small and if the rate is fast compared to the photon cavity lifetime. The efficiency of coupling modulation is resonantly enhanced because the change in the coupling coefficient required to attain a desired on-off ratio is reduced by a factor proportional to the amplitude of the intracavity field [6].

For conventional intracavity modulated microrings to achieve high modulation rates, their Q factors should be reduced. Since the efficiency of the modulator depends on the cavity finesse [6], the size of the resonator should also be correspondingly reduced. The size scaling constrains the range of tunability (through electro-optic or thermal effects) and phase-shift that can be achieved, hindering the quality of the modulator optical output.

Although highly compact, low-Q resonators can lead to high-speed intracavity modulation, there remain several benefits unique to coupling modulation. Aside from the capability for high-speed modulation beyond the linewidth limit, coupling modulation enables 1. high-extinction ratios [6, 11], 2. reduced and/or controllable chirp via the design of the coupler [11, 12], and 3. quadrature modulation by inclusion of an appropriate coupler [13]. The main drawback to coupling modulation is the *low* frequency content of the modulation signal, which can cause significant depletion or charge-up of the intracavity field, resulting in distortions in the optical output. This drawback can be mitigated by using a return-to-zero format and/or a DC-balanced encoding scheme [6].

IV. Experimental Results

We have experimentally observed a number of the essential characteristics of coupling modulation through a series of experiments in fibre ring resonators and silicon microrings [6, 11, 14, 15]. To modulate the coupling, we have used ring geometries that incorporate Mach-Zehnder interferometer couplers [8, 12]. Although similar microring configurations have been demonstrated before [16, 17, 18], their high-speed modulation, chirp, and phase modulation characteristics have not been previously recognized or studied.

Our experiments have shown that coupling modulation breaks the modulation rate limit set by the cavity linewidth, or equivalently the timescale of the intracavity dynamics, using small signal and data modulation measurements [6, 15]. We have compared the transmission of the output of coupling modulated and intracavity modulated microrings after 50 km long of optical fibres to show that coupling modulation results in reduced chirp [11]. Recently, we have shown the capability of coupling modulation for phase-shift keying [14]. The opportunity remains to investigate coupling modulation using low-loss materials and ultra-high-Q resonators.

V. Conclusion

In summary, models of microring dynamics reveal the quasi-static and non-quasi-static regimes of resonant modulation, demarcated by the photon cavity lifetime. Coupling modulation possesses desirable modulation characteristics in terms of their bandwidths, chirp, and extinction ratios not possible with typical intracavity modulation demonstrated to date. Coupling modulation opens the path toward high-speed, tunable, and extraordinarily efficient resonant modulators using ultra-high-Q microcavities.

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