Design Analysis of a High-Speed Directly Modulated Laser with Push-Pull Silicon Ring Modulators

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Abstract: We design and analyze a novel high-speed directly-modulated laser combining a pair of push-pull ring modulators. The mechanism of push-pull modulators makes the laser immune to phase-change induced wavelength chirp and other cavity-related modulation penalties.
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1. Introduction

Si microring modulators (MRMs) with a reverse-biased PN junction have recently been intensively investigated. Attribute to its small footprint, high efficiency, low loss, and CMOS compatibility, Si MRM is a promising modulator candidate for inter-chip and inter-package links having an over 10 Tb/s aggregated bandwidth. The modulation energy of an MRM can be only a few fJ/bit, but it suffers from sensitivity to manufacturing errors and ambient temperature change induced wavelength drift. Thus, both static and dynamic tunings are needed to precisely align the ring with the laser wavelength, which unfortunately adds in additional control power. In [1], a novel high-speed MRM with low power consumption was demonstrated, where the ring with reverse-biased PN junction act as not only a modulator but also a part of the laser cavity – a wavelength-selective filter. Compared with a conventional ring modulator based transmitter (Tx), which requires the minimum tuning range to cover the whole FSR of the ring, the proposed directly modulated laser (DML) only requires a small tuning range on the order of the FP mode spacing of the laser cavity, which reduces the ring tuning power significantly. However, its modulation speed was limited by the phase-change induced wavelength chirp and other cavity related modulation penalties as the reflection (amplitude and phase) of one mirror changes when ring modulation is applied.

It is challenging to obtain chirp-free modulation with the conventional microring modulators. Previously, an external cavity (EC) dual ring modulated laser using push-pull modulation has been proposed theoretically[2]. In this paper, we design and analyze the high-speed modulation of an EC DML with push-pull silicon dual-ring modulators. Low-chirp and high-speed modulation is achieved by removing intra-cavity power fluctuation, which in-turn overcomes the laser-cavity photon-lifetime limit as well as the circumventing round-trip cavity effects related to cavity phase fluctuation. The frequency-domain and time-domain modelling of the directly modulated laser operation were introduced to analyze and predict the modulation performance and the dynamic modulation.

2. Structure and operation Principle

Figure 1(a) shows the schematic of a prior art ring modulated laser with a push-pull-ring configuration. A III-V optical gain chip (or RSOA) is connected to an SOI chip via edge coupling. A 3 dB power splitter, a directional coupler or a 1x2 MMI, can be used to split the light into clockwise and counter-clockwise propagating waves. Both waves propagate through the two ring modulators. The idea to avoid wavelength chirp when the ring is modulated is to use dual-ring modulators arranged in a push-pull fashion such that the output transmission of each ring can be modulated but the combined reflection to the III/V gain section remains constant. It also allows the modulation bandwidth of the laser output to approach the ring resonators' photon lifetime limit without being limited by the laser cavity lifetime.

Figure 1(b) shows the operation principle of the EC DML. Two rings are tuned with identical resonance wavelength initially. For the modulator "ON" state, a reverse-bias voltage (or a "1") is applied to the first ring modulator with the "red" line spectra in the top transmission plot while a "0" bias is applied to the second ring with the "green" line spectra. As the two rings are connected via a second bus waveguide, both the clockwise and counter-clockwise light experience exactly the same change and recombine at the 3 dB splitter to form the reflection wave as the "blue" line shown in the top transmission plot. For the modulator "OFF" state, the bias voltages are applied in an opposite order with a "0" to the first ring and a "1" to the second ring. The through spectra of the two rings then exchange positions as shown in the bottom transmission plot. Although the order of bias of the two rings are reversed, the combined reflection wave remains unchanged as the "blue" line shown in the bottom transmission plot. Effectively, the splitter-dual-ring structure acts as one mirror of the external cavity laser. With two rings working in a push-pull fashion, the steadystate reflection from this silicon mirror to the gain chip stays unchanged for modulation "1" and "0". One thing to point out is that the reflection does change when switching between two states, but the transient time is much shorter than the carrier lifetime of the gain chip, so the impact is negligible. Also because the gain medium is not modulated, the modulation bandwidth is independent of the current-injection-related laser resonance. The lasing wavelength is determined by the overlap of the dual-ring filter resonance and the cavity FP modes. At the same time, a small amount of tuning is needed for each ring to optimize the relative position of the ring resonances and the available modulation swing[1]. The push-pull operation eliminates the cavity fluctuation completely (both intensity and phase), resulting in a low-chirp, high-speed directly modulated laser. The tradeoff is that the laser is biased off-center and hence the side-mode-suppression ratio (SMSR) can be limited, which may lead to laser mode-hopping. The SMSR can be improved by the use of a shorter overall lasing cavity with a correspondingly larger mode spacing, which will be discussed in next section.

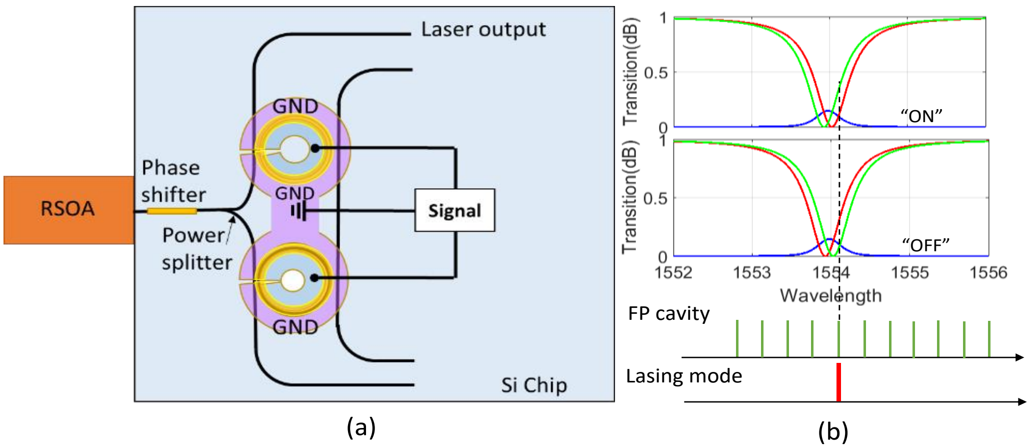

Figure 1: Configuration of the proposed dual-ring modulated laser; (b) Through port transmission for Rings 1 and 2 and overall reflection of drop to the gain chip, which does not changed during modulation, the lasing mode is determined by the overlap of the dual-ring filter with the cavity mode resonance.

3. Modelling and Analysis

We introduce frequency-domain and time-domain modelling of the EC DML operation to characterize its static and dynamic performances. The gain chip is a 600 µm long RSOA based on an InP ridge waveguide MQW structure. The SOA is biased with a constant 200 mA pumping current with high reflection facet R_{hr}=0.92. Other material parameters used in the modeling are: injection efficiency η_i= 0.65, $J_{tr} \approx 700$ A/cm, internal loss α_i = 6.5 cm^{-1}, modal differential gain Γg_0 = 45 cm^{-1}. An effective mirror model is used as detailed in [3]. A 2.2 dB coupling loss was assumed according to previous measurements from a fabricated SiNx spot-size convertors. For the Ring modulator, a lateral PN junction with a doping concentration of 4×10^{18} cm^{-3} was used inside the ring waveguide (WG) with a 5-µm radius, corresponding to a ~ 65 dB/cm transmission loss inside the ring cavity. Bus-ring gap widths were carefully designed because the performance of EC DML is sensitive to the coupling coefficients of two rings. A fixed relationship between the two coupling regions, $r_2a= r_1$, is chosen to keep critical coupling condition, where r is the self-coupling coefficient and a is the single pass amplitude transmission, with $r^2 + k^2 = 1$, k is the cross-coupling coefficient.

In Figure 2 (a)-(e), utilizing the proposed static model, we calculate the modulation bandwidth considering both the optical bandwidth and the RC bandwidth, the output power, the effective length of the ring resonators, the effective laser FP mode spacing and the effective reflection to the gain chip with different coupling power k_1^2. A 2V voltage swing at -2V common bias was used to numerically simulate the modulation operation. As we can see in Figure 2, there is a tradeoff between the output power and the modulation bandwidth. The FP mode spacing shall be large enough to guarantee the lasing mode is working at the specified detuning position. A smaller coupling power leads to a higher output power, but less reflection to the gain chip. However, the reflection should be large enough to minimize the destructive impact of reflection between the two facets of gain chip and silicon chip. A 20 dB back reflection was considered in the model. As the simulation results shown in Figure 2, a 40 GHz modulation bandwidth and 8 mW output power at "ON" state can be achieved with a coupling power of 0.08. Meanwhile, an effective FP mode spacing of ~320 pm is large enough to get a stable working point free of mode-hoping. According to the selected coupling power, the gap between the bus and ring WGs were designed to be 180 and 240 nm for a critical coupling condition. Figure 2(f) plots the L-I curves for the modulation "ON" and "OFF" state.

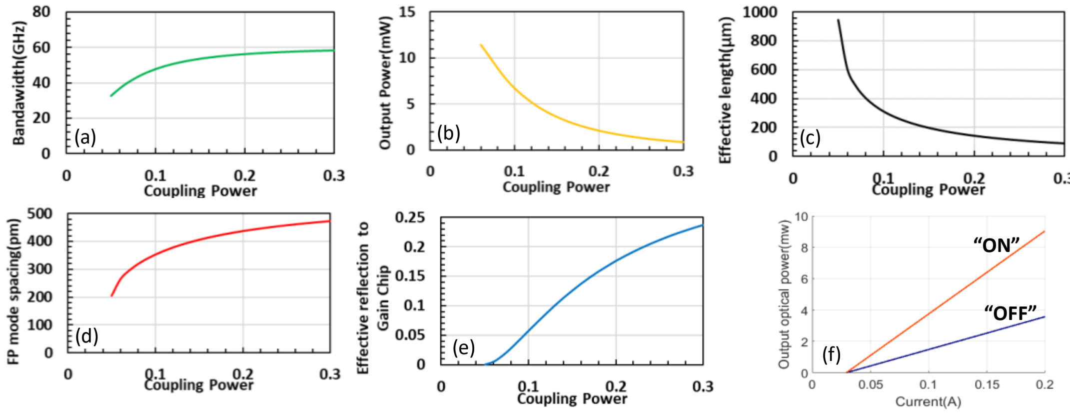

Figure 2 Relationship between modulation bandwidth(a), the output power (b),the effective length of single ring resonator (c), the effective laser FP mode spacing(d) , effective reflection to gain chip (e)with the coupling power；(f)Static L-I curve when the laser is operating on "ON" state and "OFF" state.

We also implemented a time-domain numerical model in *Lumerical* INTERCONNECT™. The SOA gain region is simulated by numerically solving coupled travelling wave equations through iterations[4]. Figure 3(a) illustrates a simplified schematic of the EC-DML. DC inputs with 200mA are used to pump the gain chip. We use a PRBS generator to send electrical modulation signals to the ring modulator to model the dynamic performances. A differential drive was applied to dual ring through a NOT element between the PRBS and NRZ generator. The working points of the push-pull MRMs were detuned from the resonance for large OMA under modulation. Figure 3(b) shows the eye diagram of 50 Gbps OOK NRZ signal out of dual-ring directly modulated laser. We simulated the modulation performance with only one ring modulator for comparison, which has the same parameters with the push-pull MRMs. A mirror model was used at the drop port for reflection. Figure 3(c) shows the eye diagram, we can see there is an obvious overshot in eye diagram, which is likely caused by the modulation induced swing of reflection to the gain chip.

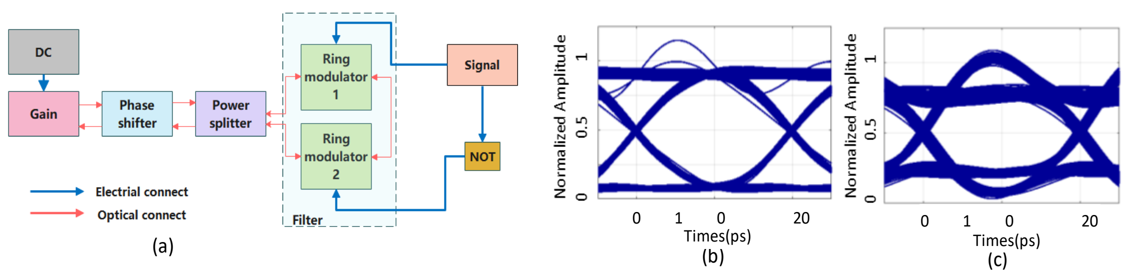

Figure 3. (a) simplified schematic of our proposed directed modulated laser; (b)50 Gbps OOK NRZ signal out of dual-ring directly modulated laser; (c) 50Gbps OOK NRZ signal out of single-ring modulated laser, mirror model was used at the drop port to realize a reflection.

4. Conclusions

In summary, we designed and analyzed a novel high-speed directly-modulated laser which combined a pair of push-pull ring modulators. A detailed analysis was applied to optimize the coupling coefficient to balance the modulation bandwidth between the output power and the lasing mode spacing. In the end, a time domain model was introduced to study the dynamic modulation performances. It is confirmed that by maintaining the cavity reflection unchanged, the principle of the built-in push-pull modulators makes the laser free of phase-change induced wavelength chirp and other cavity-related modulation penalties. A higher transmission speed more than 50Gbps can be realized by using this mechanism. The chirp-free EC-DML is promising for cost effective 5G front-hall applications.

5. References

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