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S-shaped waveguide-induced asymmetry between counter-propagating modes in a racetrack resonator

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***Abstract*— Ongoing progress in photonic integrated circuits necessitates the integration of semiconductor ring lasers (SRLs) with high performance and predictable behavior, which can be achieved when the symmetry of the SRL, which supports both clockwise and counterclockwise beam propagation, is unbalanced through loss mechanisms inside the resonator. In this work, numerical simulations were carried out on the symmetric layout of the racetrack resonator equipped with an asymmetric S-shaped internal waveguide. The simulations results were compared with the ones of analogue structures without internal waveguide showing the benefit induced by this additional element in term of the unidirectionality of the SRL.**

Keywords—ring resonator, RSoft software, finite-difference time-domain, semiconductor ring laser, photonic integrated circuits

I. Introduction

The semiconductor ring lasers (SRLs) [1] are based on a symmetric resonator which supports two counter-propagating beams, named clockwise (CW) and counter-clockwise (CCW) and can be easily embedded in photonic integrated circuits (PICs). Nevertheless, the unidirectionality in an SRL is desirable to improve the longitudinal mode purity in the pre-established direction of propagation with reduced sensitivity to the back-reflections avoiding therefore kinks in the light vs. current characteristic due to the competition between the two counterpropagating modes [1]. Different designs were proposed in literature [2]–[5] to force unidirectional operation in a resonator. An S-shaped waveguide inside the ring let to break off the natural symmetrical behaviour of the SRLs, allowing the mode conversion from CCW to CW (or vice versa). Here, we numerically simulate the asymmetric resonator constituted by a racetrack and an S-waveguide. We focus the attention on the influence of the gap distance between the racetrack and the S-waveguide [6], in order to optimize the unidirectional operation of the resonator and in turn of the SRLs.

II. Method

The asymmetric resonator was simulated with the FullWAVE module of the Synopsys© RSoft suite, based on Finite-Difference Time-Domain (FDTD) method. The main CAD layout features of Fig. 1a concern the waveguide (geometry and materials) and the launch sources. The silicon rib waveguide, 0.45 µm wide and 0.22 µm deep, surrounded by silicon oxide as background material, supports the propagation of the fundamental TE mode at 1.55 µm. It is used to describe a 86.8 µm long racetrack with a S-waveguide of half-length placed between the two directional couplers B_1 and B_2 of Fig. 1a. The major constraint for the S-branch is the radius of curvature, which was fixed in this analysis to 5 µm, value that guarantees negligible curvature losses in the considered waveguide. The behaviour at 1.55 µm of the directional couplers B_1 and B_2 was evaluated in advance; Fig. 1b shows the transmission t and the coupling κ coefficients as a function of the gap distance between the racetrack waveguide and the S-shape one. The waveguide placed at the top in Fig. 1a is evanescently connected to the resonator thank to the directional coupler C, whose coupling and transmission coefficient at 1.55 µm are shown in Fig. 1c as a function of the gap.

To simulate the spontaneous emission of a photon in the resonator, we excited the field with optical pulses centred at 1.55 µm and emitted in both the CW and CCW directions. After propagating in the ring, in the S-waveguide and in the top waveguide, the generated fields are finally collected by two monitors. The propagating in CW direction in the racetrack is measured by the monitor M_{CW} (Fig. 1a, top right) while the field resonant in CCW direction is collected by the monitor M_{CCW}, (Fig. 1a, top left). To quantify the unidirectionality of the resonator, the directional extinction ratio (DER) [4] was introduced:

$$\mathrm{DER} = 10\log_{10}(P_{CW}/P_{CCW}). \qquad (1)$$

which corresponds to the ratio expressed in decibels of the total output CW power to the CCW power captured by the two monitors.

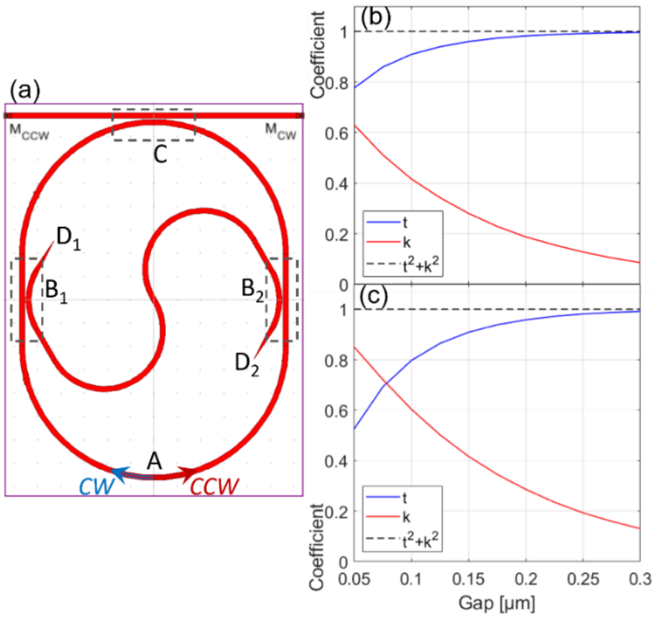

Fig. 1. (a) RSoft schematic of the consider racetrack and a S-shaped waveguide. (b,c) Coupling and transmission coefficients at λ=1.55 µm as a function of the coupler gap for the directional couplers B_1 and B_2 (b) and the directional coupler C (c).

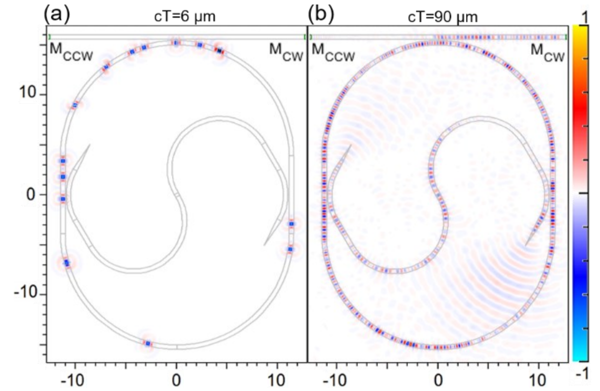

Fig. 2. Example of simulation for the device in Fig. 1a after (a) 6 μm and (b) 90 μm in unit of cT. The colours indicate the values of the field components perpendicular to the racetrack plane.

III. Results and Discussion

The simulations were carried out using the effective refractive index method (2.5D), applied for reducing the computational cost. Our goal was to investigate the influence of the gap distance between the S-waveguide and the racetrack on the DER, maximizing the unidirectionality of the resonator. The gap distance determines the coupling of radiation into the S-waveguide, as shown in Fig. 1b, hence the fraction of power that propagates in the S-waveguide. On the other hand, the coupling distance in C was set to 0.1 μm allowing to reduce the simulation times. Each simulation was performed exciting 32 electromagnetic sources (16 in CW direction + 16 CCW) simultaneously from 16 random positions along the racetrack. Fig. 2a shows an example of launch positions randomly selected along the racetrack in case of 0.1 μm gap for the B coupling regions. In detail this figure displays the field distribution after 6μm in unit of cT (T time, c speed of light in a vacuum).

Fig. 2b, shows the field distribution after a time of 90 μm×c, and highlights the conversion from CCW field into in CW one. Part of the CCW field evanescently coupled to the S-waveguide in B_1 and B_2 regions is re-coupled in opposite coupling area of the racetrack (B_2 and B_1) as CW field. The remaining field is spread outside the waveguide (radiation loss) by the tapered ends D_1 and D_2, avoiding back reflections. On the other side, the CW field is reinforced by the converted CCW field and attenuated by the coupling field to the S-waveguide and expelled outside by D_1 and D2. Fig. 3 shows the ouput optical spectra calculated at the monitors of the FDTD simulation for the case reported in Fig. 2. The different amplitudes of the optical spectra highlight the asymmetric behaviour between the two counter-propagating fields. To improve the accuracy of the results, the simulation was repeated 20 times, placing the launched fields in random position in the waveguides and keeping fixed the monitors locations. The average DER is (3.157 ± 2.760) dB.

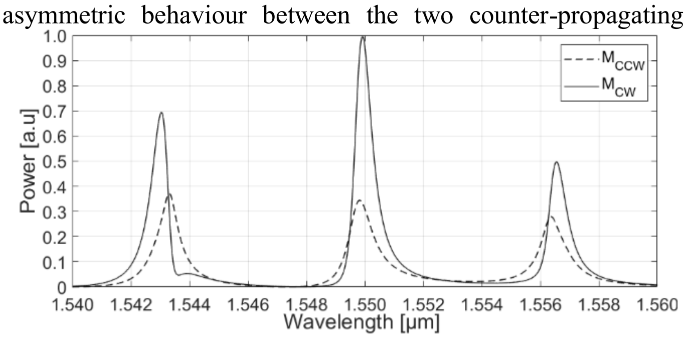

Fig. 3. Emission spectra relatives to the simulation of the launch configuration shown in Fig. 2a. The CCW and CW field are measured from the monitors M_{CCW} and M_{CW}, respectively.

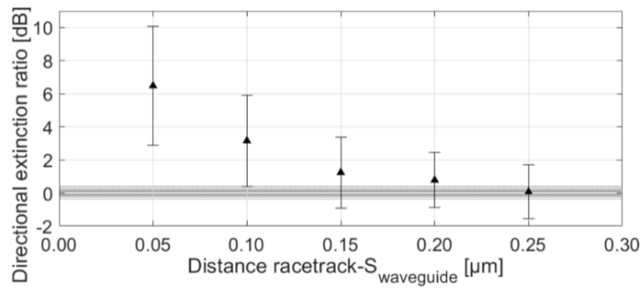

Fig. 4. Average and standard deviation of the directional extinction ratio as a function of the gap of couplers B_1 and B_2, estimated over 20 simulations. The horizontal grey bar represents the value obtained without the S-shaped waveguide when CW and CCW fields have therefore the same power.

Further simulations were carried out by varying the gap between the resonator and the S-waveguide from 50 nm to 250 nm, preserving the original optical lengths of the racetrack and of the S-waveguide. Fig. 4 summarizes the simulation results plotting the average and the standard deviation over 20 runs of the DER calculated in correspondence to the resonant peak around 1.55 μm as a function of the gap distance; the grey bar shows the calculated DER value of the symmetric resonator without the S-shaped waveguide (0.059 ± 0.261 dB). It is noticeable the unidirectional behaviour of the resonator induced by the S-branch, especially when the chosen gap is smaller than 100 nm.

IV. Conclusions

We proposed a method to quantify the effect of an S-waveguide inside the racetrack to unbalance the CW and CCW fields propagating in the resonator, promoting the CW field with respect to the CCW ones. The device unidirectionality is improved reducing gap between the waveguides, thus increasing the coupling coefficient. The unidirectionality factor DER obtained with small gap distance is expected to be enhanced when operating in a SLR, above threshold [1].

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