Integrated optical gyroscope

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In this work we present and discuss two different designs of a miniaturized optical gyroscope, realized as application specific photonic integrated circuits (ASPICs). The first one is the classical interrogator of a fiber-optic Sagnac interferometer. The circuit comprises a DBR laser as a light source, PIN photodiodes as detectors and an electro-optic phase shifter, which enhances the sensitivity of the gyroscope system. The second approach is based on a ring laser with four semiconductor optical amplifiers. The resonator length, which determines the sensitivity of the device, is increased by application of a Mach-Zehnder switch within the laser cavity.

Introduction

Gyroscopes are an essential part of modern airplanes, helicopters, naval vessels, missiles and space shuttles. Nowadays they are also applied in motor vehicles, Segway transporters and cell phones. There are different kinds of contemporary gyroscopes: spinning mass, vibrating and optical [1]. The first use a mass spinning around an axle, while the second are based on the Coriolis effect that induces coupling between two resonant modes of a mechanical resonator. On the other hand, optical gyroscopes use the Sagnac effect [2], observed as a phase shift between two waves counter-propagating in a rotating ring resonator or an interferometer, which is proportional to the loop angular velocity.

There are several important advantages of optical gyroscopes in comparison to the mechanical counterparts. First of all, as they have no moving parts, they do not require a mechanical engine. Furthermore, due to a very short warm up time, they can be switched on and off almost instantly. The combination of these two features causes that the power consumption can be significantly reduced. Additionally, the dimensions and weight of the device may be significantly reduced, which is a key feature when aviation applications are of concern. There are two most popular schemes of operation of all-optical gyroscopes, both based on the Sagnac effect in an optical medium. The first one uses a passive fiber loop, into which an optical signal from a laser or from a superluminescent LED is coupled [3], while the other uses a laser in a ring resonator configuration [4].

It should be noted that despite many trials [1], contemporary optical gyroscopes are still manufactured using discrete optoelectronic and fiber-optic based devices. In this work we propose different concepts, which use InP-based generic foundry technologies that have been developed over the past few year [5]. Two photonic integrated circuits were designed, one as an integrated module serving as an interrogator for an interferometric fiber-optic gyroscope (IFOG), second as a fully integrated ring laser gyroscope (RLG).

Chip design

The circuit scheme of the IFOG interrogator is presented in Figure 1a. The laser light is injected into a fiber coil through a cascade of 2×2 couplers, which guarantee that the two beams will travel exactly the same optical distance between the source and the detector (with the same number of “cross” and “bar” transitions through the couplers). When the coil is rotating, the two counter propagating beams experience different phase shifts, which influences the intensity of the interference signal at the output. The signal is then recorded on the other side of the couplers by a photodetector and further analyzed. For a circular coil the phase difference follows the equation (1.1) [1]:

$$\Delta\varphi = \frac{8\pi^2 R^2}{c\lambda} k\Omega$$

where R is the radius of the coil, k is the number of fiber turns in the loop and Ω is the angular velocity of the coil.

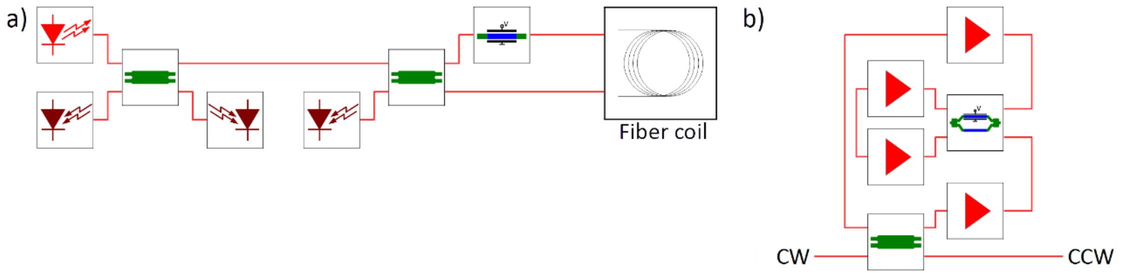

Fig. 1. Circuit scheme of an integrated interrogator for an interferometric fiber-optic gyroscope (a) and an integrated ring laser gyroscope (b).

Figure 1b presents the circuit scheme of the integrated ring laser gyroscope. It uses four sections of semiconductor optical amplifiers (SOA) as the laser active medium. An amplitude modulator in Mach-Zehnder configuration is applied to increase the effective resonator length and thus increase the sensitivity of the gyroscope system. To achieve it, the modulator has to be fixed to transmit the light to the “cross” port.

While rotating, the resonance wavelength is different for CW and CCW orientation due to the Sagnac effect. The frequency difference follows the equation (1.2) [1]:

$$\Delta\nu = \frac{4a\nu}{pc}\Omega$$

where p is the perimeter and a the area of the resonator. The frequency shift can be extracted by detecting the beating signal, which is a result of interference of two laser beams of slightly different wavelengths.

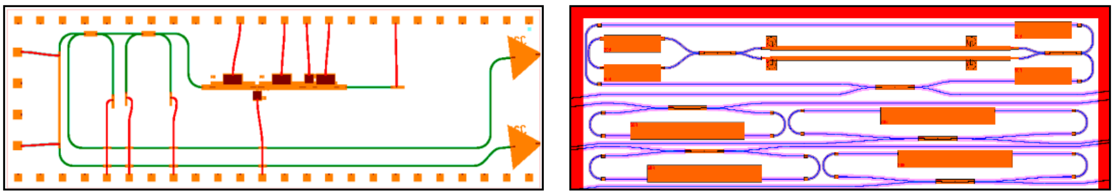

Fig. 2. Mask layout of the integrated interrogator for an interferometric fiber optic gyroscope (left) and the integrated ring laser gyroscope (right).

The mask layouts of the designed chips are presented in Figure 2. The design of the IFOG interrogator uses a DBR laser (constructed from an SOA, a booster SOA, tunable DBR gratings and a phase modulator), 2×2 MMI couplers, an electro-optic phase modulator, PIN photodetectors, passive waveguides and waveguide transition elements. The cell dimensions are 6 mm × 2 mm. The chip was designed according to a recently developed generic packaging scheme. The laser electrodes and PIN photodiodes are connected through metal tracks to the electrical DC ports (on the top and at the bottom of the chip). The electro-optic phase modulator is connected to the RF ports (on the left side). Two angled spot-size converters are used for efficient coupling of the input/output signals with

two SMF fibers. The chip was designed and fabricated using the Oclaro generic foundry service [5]. After the fabrication the chip was packaged in an experimental generic packaging process by Linkra.
Integrated ring laser gyroscope was designed in the generic foundry service provided by SMART Photonics [5]. The circuit uses four amplifiers (l_{SOA1} = 500 μm), a Mach-Zehnder amplitude modulator (comprising two 2×2 MMI couplers and two electro-optic phase shifters). The ring resonator is formed by looping the waveguides and connecting them to a 2×2 MMI, which provides also the outputs for the CW and CCW signals. The total ring resonator length is around 20 mm, placed on the area of 4.6 mm × 0.8 mm.
Apart from the laser with an applied modulator within the resonator, four simpler variants of ring lasers were designed. All of them comprise single amplifier sections (l_{SOA1} = 1000 μm) and differ in the resonator length (3.5/4.1/4.7/5.3 mm).

Characterization

The measurement setup comprised current sources for driving amplifiers and Bragg gratings and source meters for biasing PIN photodiodes and electro-optic phase shifters. The output signal was detected either by power meters or an optical spectrum analyzer.
Figure 3. presents initial measurement results of the IFOG interrogator active elements. It shows a characteristic of the DBR laser power as a function of the current injected to the gain section, while the booster was driven with 30 mA of current. The maximal measured power was 0.52 mW and 0.71 mW (I_{SOA} = 100 mA), depending on the output. The difference (1.4 dB) may be a result of imbalance of the on-chip MMI couplers. It may be also caused by a difference in the coupling efficiency between the outputs. The signal measured on chip at 100 mA was equal to 6.1 mW. Taking into account splitting and insertion loss of the second MMI (3 dB + 0.8 dB) and waveguide attenuation (2.4 dB), the coupling loss between the chip and the optical fibers may be estimated at 3-4 dB.

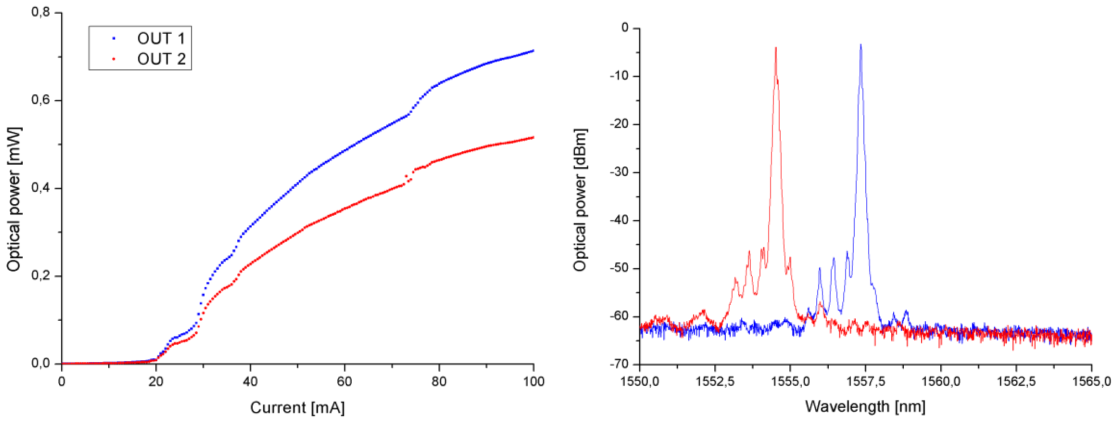

Fig. 3. Measured laser power characteristic (left) and output spectra (right) of the DBR laser of the IFOG integrated interrogator.

Figure 3. presents also the output spectra of the laser, while powering the gain section with a current of 100 mA and the booster with 25 mA. When the booster is driven with a current exceeding 30 mA, the spectral properties of the laser signal degrade, most likely due to thermal effects and their influence on the cavity modes (the booster is located very close to the front DBR grating). The laser wavelength is λ_1 = 1557.3 nm and can be tuned down to λ_2 = 1554.5 nm ($\Delta\lambda$ = -2.8 nm) by driving the rear DBR with 3.4 mA.
Figure 4. presents the results of characterization of the second discussed chip – integrated ring laser. Due to high cavity loss, which is a result of the resonator length (L ≈ 20 mm),

the threshold current is around 25 mA per single SOA (100 mA in total). The power of the two signals (CW and CCW) is comparable up to 90 mA of injection current, above this level the CCW mode dominates. This effect, combined with significant power variations above 90 mA, limits the maximum power that can be obtained for this laser in application as a gyroscope – the two counter-propagating beams should have comparable optical powers in order to detect a decent beating signal.

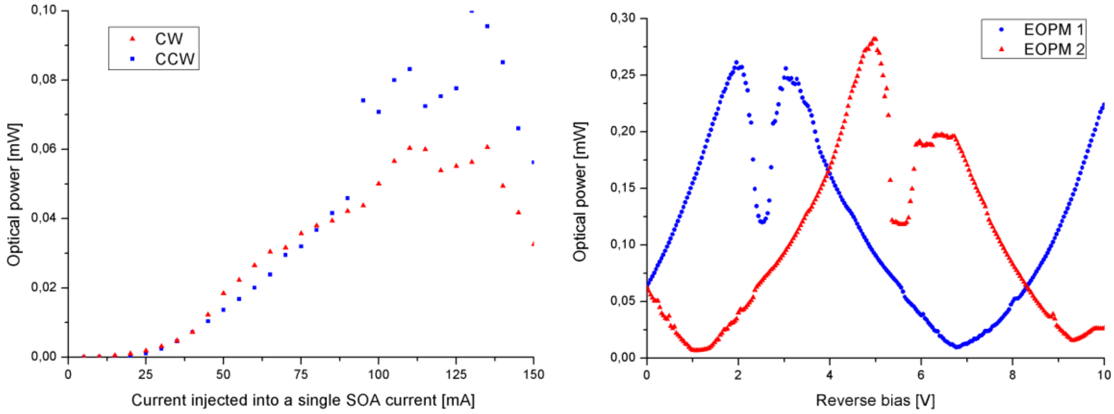

Fig. 4. Measured laser power characteristics versus current injected into a single SOA section (left) and versus reverse bias applied to the EOPM sections (right).

The LI characteristic was measured while grounding the electro-optic phase modulators (EOPM). In order to verify how the Mach-Zehnder modulator influences the output signal of the laser, the phase sections were reversely biased in the range from 0 V up to 10 V and the output power was monitored. Figure 4. presents the obtained results. The maximum power has increased from 62 μW to 282 μW (6.6 dB of improvement). The dips in the characteristic are most likely due to distortions of the phase relations of the ring laser modes. The shape of the characteristic also suggests that the modulator is not balanced in phase and therefore needs to be controlled to obtain stable laser action.

Summary

Two photonic integrated circuits, a fiber loop interrogator and an integrated ring laser, were demonstrated and discussed. The chips were realized in recently developed generic foundry processes. The initial measurements confirmed the general idea of the circuits and provided important feedback towards optimization of the device.

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