Chapter 54
Innovative Integrated-Optic Resonator for Angular Rate Sensing: Design and Experimental Characterization

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Abstract In this paper we report on the design, fabrication and characterization of an integrated-optic spiral resonator for angular rate sensing applications. The spiral resonator design has been optimized through a parametric analysis and a minimum angular velocity of about 10°/h, suitable for aerospace applications, has been theoretically predicted. The resonator has been fabricated in silica-on-silicon technology and characterized. Experimental results are in good agreement with the theoretical predictions.

54.1 Passive Resonator Angular Velocity Sensor

During the last decades optoelectronic technologies have enabled the development of very sensitive gyroscopes based on Sagnac effect [1, 2].

Integrated-optics for angular rate sensing may solve some open issues in gyro technology such as the need of both weight and size reduction, cost lowering, power consumption decrease, thermal effects limitation, and reliability increase. Photonic technologies could allow the integration of a gyroscope on a single chip and this can be surely pointed out as a very interesting research target especially in the framework of micro- and nano-satellites development.

In passive integrated optical angular rate sensors, an optical cavity is excited by two beams counter-propagating in clockwise (CW) and counter-clockwise (CCW) direction. When the gyro rotates, the resonance frequencies of the cavity relevant

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to the two propagation directions are not equal. The difference between them is proportional to the angular rate and increases by enlarging the optical path. Passive integrated optical gyros typically employ a low-loss large-radius ring resonator having a high quality factor as sensing element. Silica-on-silicon technology allows to fabricate very low-loss (<0.1 dB/cm) optical waveguides operating at 1.55 μm. Propagation loss of these waveguides depends also on index contrast Δ between the guiding and the cladding layer and values around 0.01–0.03 dB/cm has been achieved for $\Delta < 1\%$. Bending loss exponentially decreases with curvature radius, so a curvature radius larger than a few millimetres is required to achieve negligible bending loss.

54.2 Integrated-Optic Spiral Resonator

The innovative integrated optical resonator, here proposed, consists of a waveguide in a spiral closed loop. This geometry has been chosen with the aim of increasing the optical path length. The spiral resonator is coupled to two straight bus waveguides, as it is shown in Fig. 54.1, in order to allow the propagation of two counterpropagating beams. When light is coupled to the spiral loop through the input waveguide, it builds up in intensity over multiple round-trips due to constructive interference. Only some wavelengths resonate within the spiral loop.

The spiral geometry proposed in [3] allows to enhance the quality factor and Sagnac effect if compared to the ring geometry because a longer optical path can be realized in the same area. On the other hand, silica-on-silicon technology allows to reduce propagation loss so further improving much more the quality factor.

Through port and drop port are, respectively, the output taken on the same input waveguide and the output on the adjacent waveguide. Each coupler can be modelled as a transfer matrix derived by the coupled mode theory [4].

The spectral response of the cavity has been obtained by using the transfer matrix method, neglecting the coupling effect due to the interaction of the two counter-propagating modes because they are supposed to be not simultaneously launched in [5, 6].

54.3 Detection Limit Optimization of the Spiral Resonator Based Sensor

The minimum detectable angular velocity ($\delta\Omega$) of a passive ring resonator gyro is limited by the shot noise at the photodetector included in the read-out system and is expressed as [3]:

$$\delta\Omega = \frac{2\pi}{L}\frac{1}{\sqrt{\eta P}}\frac{\sqrt{hc^3B}}{\sqrt{2\lambda}}\frac{1}{Q\sqrt{\rho}}$$

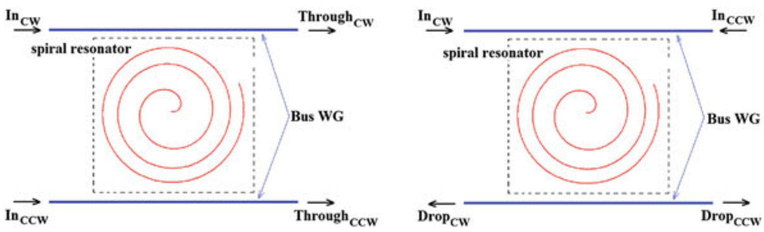

Fig. 54.1 Through (*left*) and drop (*right*) port configuration of the spiral resonator

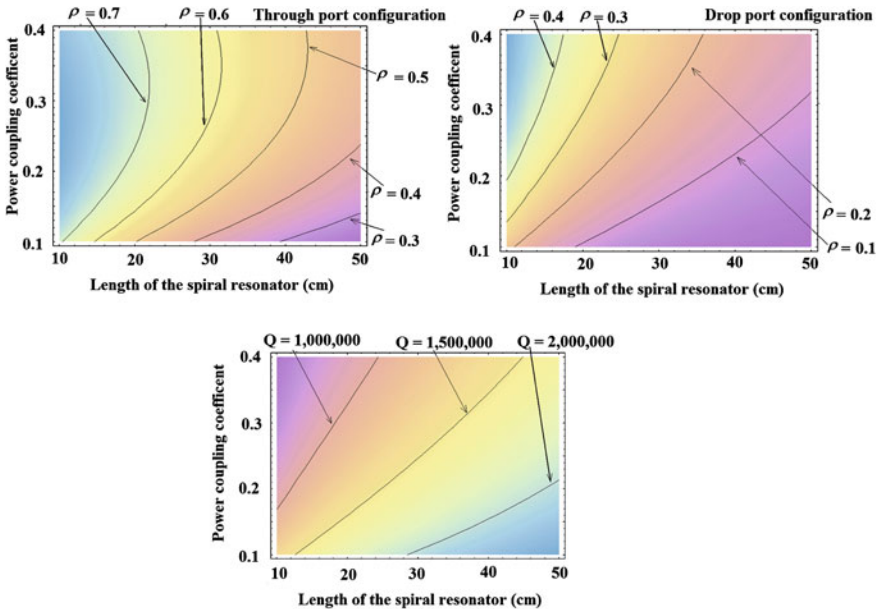

Fig. 54.2 Resonance depth as function of power coupling coefficient and spiral length for through port (*top left*) and drop port (*top right*). *Q*-factor (*bottom*) as function of power coupling coefficient and spiral length

where λ is the operating wavelength, c is the light velocity in the vacuum, h is Planck's constant, P is the optical power at the input of the photodetector, B is the sensor bandwidth, η is the photodetector quantum efficiency, L is the spiral perimeter, Q is the resonator quality factor and ρ is the resonance depth. To reduce $\delta\Omega$, Q needs to be increased as well as the resonance depth.

Both resonance depth and the quality factor variations as a function of the spiral resonator length (ranging from 10 to 50 cm) and of the power coupling coefficient between the resonator and the bus waveguides (in the range 10–40%) have been

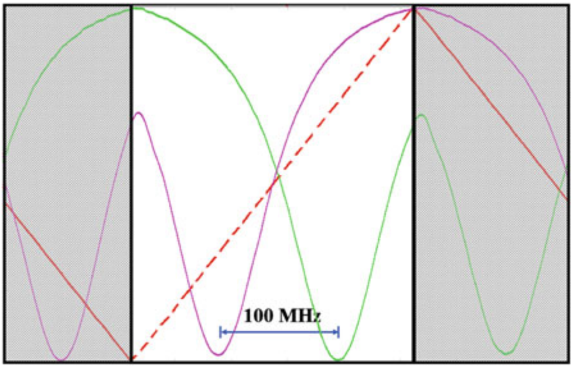

Fig. 54.3 Through port spectral response of the spiral silica resonator for the two propagation directions (*green* and *purple*) when the sawtooth signal (*red*) is applied to the laser module

investigated. The results of this parametric analysis are reported in Fig. 54.2. Propagation loss of the silica-on-silicon waveguide (=0.1 dB/cm) and guiding structure effective index (=1.457) have been kept constant.

To reduce the detection limit, a good trade-off between quality factor and resonance depth has to be assured for each possible configuration (drop port and through port).

By assuming a spiral length longer than 30 cm, quality factors higher than 10^6 are achievable although the resonance depth cannot be optimized at the same time. Since the *Q*-factor stronger influences the sensitivity, the spiral has been designed to optimized it. A resolution in the range 10–100°/h can be obtained. By reducing propagation loss until 0.01 dB/cm, the resolution can be lowered in the range 1–10°/h. As an example, assuming drop port configuration, for a resonator length of 38.4 cm the sensitivity is 28.5°/h when propagation loss is 0.1 dB/cm and the coupling strength is 20%. By assuming the same length, sensitivity becomes 14.8°/h when propagation loss is 0.05 dB/cm and the coupling strength is 10% and 3.0°/h for propagation loss of 0.01 dB/cm and coupling strength of 2%.

54.4 Experimental Characterization of the Spiral Resonator

The spiral resonator has been fabricated at CIP (Centre for Integrated Photonics, Ipswich, UK) by using silica buried waveguides with a core size of $6 \times 6\ \mu m^2$ and an index contrast of 0.75% at $\lambda = 1.55\ \mu m$ [3]. Figure 54.3 shows the experimental results obtained for a 42 cm long spiral having through port configuration, with a coupling coefficient of 40%.

The spectral response has been measured by using a thermally tuneable fiber laser having a linewidth <1 kHz, an acousto-optic frequency shifter driven by a signal generator, a variable optical attenuator, a 50/50 fiber splitter, a polarization controller, two photodetectors, an oscilloscope and a signal generator. A sawtooth signal having a frequency of 0.2 kHz has been applied to the laser module for frequency modulation. The frequency of the two optical signals exciting the cavity varies accordingly to the saw-tooth waveform and the two frequencies exhibit a fixed difference of 100 MHz due to the presence of the acousto-optic frequency shifter.

From the measured spectrum a quality factor Q equal to 1.55×10^6 has been calculated. This result, better than the simulated Q value ($=1.4 \times 10^6$) is due to the lower propagation losses of the fabricated waveguides estimated to be about 0.08 dB/cm. Thus, a sensitivity value of about 10°/h has been demonstrated.

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