Slow-light rotation sensors

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Exploiting the flexibility, compactness, and optical properties of photonic-resonance-based structures enables fabrication of miniature yet sensitive gyroscopes.

Precise positioning and motion tracking are enabling development of key technologies in numerous fields of research and applications such as control, navigation, stabilization, and positioning systems for robotics, medical-imaging applications, virtual reality, computer games, and many more. While rotation sensing can be based on both mechanical and optical effects, optical gyroscopes provide the highest sensitivity and accuracy.

Although the details may vary depending on the specific implementation, all optical rotation sensors exploit the Sagnac effect, i.e., the interference pattern resulting from the different phase shifts of waves propagating in a circular path along and opposite the direction of rotation. The classical Sagnac phase shift is determined solely by the angular velocity, the optical frequency, and the area enclosed by the closed-loop optical path, and completely independent of the medium’s other properties such as the index of refraction and its dispersion properties.

This century-old result has been the subject of ongoing debate for several decades, both because of its fundamental nature and because it inherently limits the feasibility of attaining highly sensitive miniaturized rotation sensors. Specifically, it implies that the only ways to enhance the sensitivity and accuracy of optical gyroscopes are to either increase the optical frequency or enlarge the gyro’s area. In practice, both approaches are limited.

Recent studies have pointed out the advantages of exploiting the Sagnac effect, generated by electronic resonances, in slow and fast-light media (i.e., in which the group velocity is substantially smaller or larger than the speed of light) for fabrication of ultrasensitive optical gyroscopes. However, material properties based on slow/fast-light media suffer from inherent limitations and drawbacks. In particular, such systems are bulky, lossy, require very low temperatures, and are limited to specific wavelengths according to the material’s electronic and optical properties. Instead, we have been focusing on photonic-resonance-based structures, taking advantage of their flexibility, compact dimensions, and excellent optical properties to develop new concepts for highly accurate miniature gyroscopes.

We have developed a new class of optical rotation sensors using coupled-resonator optical waveguides (CROWs). Light propagating through a CROW (see Figure 1) slowly tunnels from one resonator to the next while circulating many times inside each cavity. This circulation determines the CROW’s unique dispersion relation (see Figure 2) and its ability to slow down light. Under mechanical rotation, the light’s circulation in each cavity significantly enhances the accumulated Sagnac phase shift, thus providing higher sensitivity to rotation, which can be exploited.

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An interesting feature of CROWs that is extremely important for rotation sensing is that light circulates in opposite directions in adjacent resonators (see Figure 1). While completely insignificant in stationary CROWs, rotation of the waveguide effectively induces opposite-sign resonance-frequency shifts in adjacent resonators.\(^7\) Thus, instead of arrays of identical resonators, rotating CROWs are effectively composed of pairs of adjacent resonators with alternating resonance-frequency shifts, where the shift magnitude depends linearly on the rotation rate. The impact on the CROW dispersion relation is profound: a rotation-induced stop band is formed in the middle of the (stationary) CROW passband (see Figure 2). The formation of this stop band indicates that light at these frequencies is attenuated exponentially as it propagates through the rotating CROW. Figure 3 shows the spectral transmission factor of a 25-microring-long CROW for various rotation rates. We found\(^7\) that the transmission decreases exponentially as the rotation rate increases (as opposed to a linear decrease in conventional Sagnac gyros), thus providing a new route for the construction of miniature yet highly sensitive rotation sensors.

As an alternative approach, we employed the CROW as the Sagnac loop in a conventional gyro\(^6\) (see Figure 4). The strong attenuation in the center of the passband is also accompanied by strong phase shifts that depend on the direction in which the light propagates in the slow-light Sagnac loop. Since the rotation modifies the CROW’s dispersion properties (unlike the material’s dispersive properties), the slow group velocity can be used to substantially enhance the sensor’s sensitivity without sacrificing the small footprint.

In summary, slow-light structures provide a new and fresh approach for realizing ultracompact, highly sensitive optical rotation sensors and gyroscopes. Fabrication of such sensors, employing microring resonators, can be achieved using contemporary microfabrication technology, thus rendering the concept highly applicable and practical. In addition to experimental demonstration of the concept, we will next address fabrication tolerances and develop methods for post-tuning our devices to achieve higher sensitivities and improved repeatability.

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**References**


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