Fiber ring lasers offer a simpler solution for nanoscale sensors

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A whispering gallery mode resonator inserted into the loop of a fiber ring laser promises a simpler, cheaper, higher-resolution detector for applications in ultra-sensitive sensing.

Certain applications in medicine, biodefense, drug discovery, and environmental monitoring depend on the ability to detect low-concentration pathogens and nanoscale viruses. Devices known as whispering gallery mode resonators (WGMRs) have been studied extensively in recent years for applications in ultra-sensitive sensing. Named after the famous Whispering Gallery in St. Paul’s Cathedral in London—where a whisper spoken into the wall can be clearly heard on the opposite side of the room—WGMR devices trap light within a submillimeter-sized, spherical, dielectric resonator by total internal reflection. The resonance frequency of these devices shifts when there is a change in the refractive index in a region that overlaps with the resonant mode. This occurs, for example, when the external index changes (the device then works as a refractometer) or when biomolecules binding to the resonator surface change the local index (acting as a label-free biosensor).

The typical implementation of a sensing system based on high quality ($Q$) factor WGMRs requires a finely tunable laser with a linewidth narrower than the monitored resonance. Such a setup is shown in Figure 1. The laser light is coupled to the resonator. The output of the coupler is sent to a photodiode connected to an oscilloscope. By periodically scanning the laser, the position of a WGM resonance—corresponding to a dip in the transmission—can be carefully monitored. The $Q$ factor, which is inversely proportional to the resonance linewidth, is a key parameter that affects the sensor sensitivity. Narrower linewidth leads to higher sensor resolution, e.g., its ability to discriminate a small frequency shift associated with the binding of a few molecules. The smallest shift that can be accurately measured is equal to a fraction of the cavity linewidth.

We propose a simpler, less-expensive approach based on detecting the shift of a fiber ring laser containing a WGMR in its loop. A fiber loop containing an erbium-doped fiber amplifier (EDFA) is closed on the microsphere via two couplers. A portion of the light circulating in the loop is extracted with a tap coupler and sent to a Fabry-Pérot (FP) analyzer in order to accurately monitor the position of the fiber ring laser line (see Figure 2).

Comparing the shift of the microsphere resonance with that of a ring laser line stabilized with the same microsphere, we found they are practically identical. Our experimental setup combined the configurations shown in Figures 1 and 2. We used a 250µm silica microsphere resonator fabricated by melting the tip of a standard optical fiber using the electric arc of a fiber splicer. Its $Q$ factor was intentionally kept low ($\sim 10^6$) to mimic the typical value of coated microspheres used in biosensing applications. Since the microsphere essentially behaves as an etalon, we observed single-mode lasing of the fiber ring on the FP. The lasing wavelength observed on an optical spectrum analyzer was $\sim 1532$nm, corresponding to the peak gain of the EDFA. The resonance line spacing between microsphere fundamental WGMs was $2.1$nm ($260$GHz) with a linewidth of $\sim 0.1$GHz (loaded $Q = 2 \times 10^6$). We monitored a resonance close to the lasing wavelength with the highest transmission.

We found that the resonance and laser line undergo the same shift, as shown in Figure 3 (the slope is equal to 1.01 ± 0.04).

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The laser line and resonance detuning were compared within a 1GHz overall shift. In general, a few gigahertz is the typical scanning range for many sensing applications. We induced this shift through a thermal effect by placing the microsphere in a homemade thermostatic cell. It is important to note that while the temperature-induced resonance shift is the result of a bulk effect inside the silica sphere, the proposed sensing mechanism does not depend on how the shift is produced. As previously stated, this effect takes place whenever a refractive index change occurs in a region probed by the WGM (including in its evanescent tail).

Because the laser line is typically narrower than the ‘passive’ resonance linewidth, as shown in previous work, increased sensor resolution is possible. We evaluated our fiber ring laser linewidth with a heterodyne beat measurement. A comparison with the corresponding loaded microsphere resonance showed a line narrowing of at least two orders of magnitude. An improved resolution for a WGM-based sensor would then be possible by monitoring the ring laser line shift instead of the microsphere resonance shift, which makes finding the location of the resonance peak easier.

For practical applications, a convenient (in terms of free spectral range and finesse) FP interferometer (as shown in Figure 2) rather than a heterodyne detection scheme should be used. The periodical response of the FP allows easy scanning over a range larger than its free spectral range. The only other piece of equipment needed is a fiber amplifier. Therefore, the proposed system is more convenient than that based on a finely tunable semiconductor external cavity laser. One potential drawback is the dual coupling scheme, which is not straightforward to implement on a microsphere.

Using a different approach, the microsphere itself could act as laser cavity if properly doped with ‘active’ material, e.g., erbium ions (Er³⁺). High sensitivity using this approach in an on-chip configuration was recently demonstrated. In this case, however, control of the pump coupling is critical. Also, the potentially high operating temperature of the microsphere would be detrimental for biosensing applications.

In conclusion, we demonstrated the potential of a stabilized erbium-doped fiber ring laser for intracavity sensing using a WGM microsphere resonator. In the proposed scheme, the microsphere acts as an etalon with the laser line following its transmission peak when shifted. We measured the same shift for the laser line and for the cavity resonance. Whenever the sensing transducing mechanism is based on monitoring the position of the WGM resonance, this approach may be implemented using simpler and more convenient equipment. Additionally, an improved sensor resolution is possible because of the narrower laser linewidth. Future implementations of this approach will include application to integrated disks, which typically exhibit rather low quality factors.

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