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Whispering Gallery Resonators for Optical Sensing

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ABSTRACT

In recent years, whispering gallery mode devices have extended their functionality across a number of research fields from photonics to sensing applications. Here, we will discuss environmental sensing applications, such as pressure, flow, and temperature using ultrahigh Q-factor microspheres fabricated from ultrathin optical fiber and microbubbles fabricated from pretapered glass capillary. We will discuss device fabrication and the different types of sensing that can be pursued using such systems. Finally, we will introduce the concept of using cavity ring-up spectroscopy to perform dispersive transient sensing, whereby a perturbation to the environment leads to a frequency mode shift, and dissipative transient sensing, which can lead to broadening of the mode, in a whispering gallery mode resonator.

Keywords: optical sensor, whispering gallery mode, microsphere, microbubble, ultrathin optical fiber, nanofibers

1. INTRODUCTION

Whispering gallery mode (WGM) resonators are widely used for a number of sensing applications[1]. The very high optical quality factor (Q-factor) that can be achieved and the small optical mode volume of whispering gallery resonators (WGRs) mean that the modes are very sensitive to even the smallest change in environmental parameters. Such resonators have been used to measure fluctuations in temperature[2,3], pressure[4], stress[5], refractive index[6] etc. Ultrahigh sensitivity sensing in whispering gallery resonators relies on a dispersive frequency shift of the optical modes due to the environmental perturbation[7]. Aside from this frequency shift, the mode's optical linewidth may increase through the introduction of dissipation to the system[8]. If mode coupling is present, mode splitting may also be observed[9]. We have exploited cavity ring-up spectroscopy to develop a method for performing both dispersive and dissipative transient sensing in a whispering gallery resonator[10].

2. WHISPERING GALLERY RESONATOR FABRICATION

We have used solid silica microspheres or hollow silica microbubbles for most of our sensing related work[2-4,10-13]. Figure 1 is a schematic representation of the method we use to fabricate single, silica microspheres from a section of optical fiber

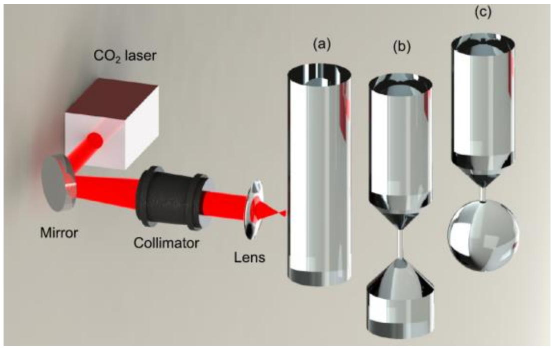

Figure 1. Silica microsphere fabrication setup. A CO$_2$ laser is collimated and focused using a lens. (a) A section of silica fiber is placed at the focal point of the lens and its position is controlled using a 3D stage. The fiber reduces in size and forms a shape as illustrated in (b). (c) The material below the narrow fiber region is reheated to form a sphere. Figure not to scale.

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using a focused CO_2 laser beam. The microsphere is formed by tapering and melting the section of fiber; the final device is attached to a thin stem, the thickness and length of which we can control as desired. Such microspheres are used in our transient sensing proof-of-principle work[10].

The fabrication method for the microbubble resonators is depicted in Fig. 2. A silica capillary is pretapered and then expanded into a bubble shape by applying internal aerostatic pressure using nitrogen gas while heating using a CO_2 laser. Such resonators are used for temperature[2,3] and pressure sensing[4] and we have achieved ultrathin walled bubbles using this fabrication technique[4]. The microbubble devices are very versatile and we can exploit the aerostatic pressure tuning for a range of applications[13].

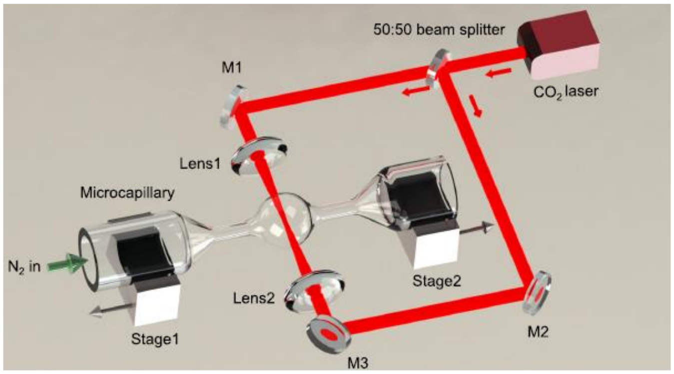

Figure 2. Microbubble fabrication setup. A CO_2 beam is focused using two lenses (Lens1 and Lens2) onto a tapered silica glass capillary while internally pressurizing it using nitrogen gas. M1, M2, M3: mirrors.

Regardless of the type of whispering gallery mode resonator used, light is coupled into it via a tapered optical fiber, generally fabricated using a hydrogen:oxygen flame heat-and-pull rig. A typical coupling setup for a microsphere resonator is illustrated in Fig. 3. Both the resonator and tapered fiber are on translation stages in order to optimise the coupling between the two.

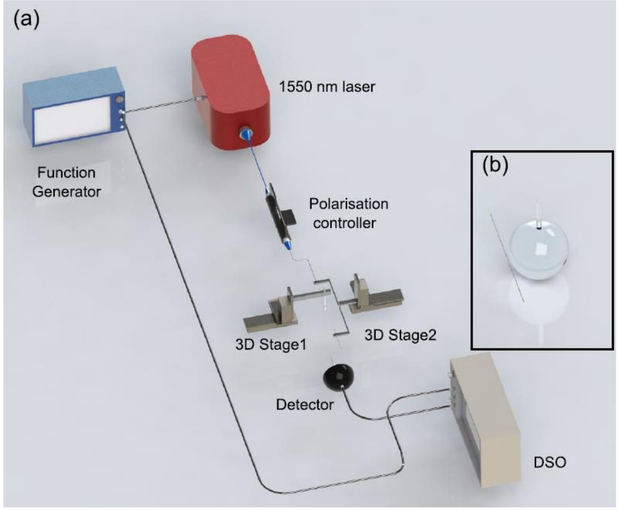

Figure 3. (a) Schematic of the fiber taper-whispering gallery resonator coupling setup. (b) Fiber taper and a microsphere cavity.

Aside from passive resonators, we have also created active devices by coating a tapered silica capillary with an erbium-ytterbium doped phosphate glass layer and this system has been used for flow sensing[11,12]. Further details on two of our sensing experiments are contained in the following section.

3. WHISPERING GALLERY MODE OPTICAL SENSORS

3.1 Pressure Sensing

In our pressure sensing work[4] we used a hollow microbubble resonator, the fabrication of which is depicted in Fig. 2. We have been able to exploit the pressure sensitivity of these devices for linear laser tuning[13]. We used the Pound-Drever-Hall method to lock a tunable laser around 1550 nm to a whispering gallery mode of the microbubble. Linear tuning of the mode via aerostatic pressure led to linear tuning of the locked laser with almost zero hysteresis evident. The WGM shift was around 58 GHz/MPa and the limit-of-detection was 2×10^{-4} MPa. We also tested the longer term stability of the pressure tuning for different input pressures. We noted that the noise on a typical WGM had a maximum standard deviation of 36 MHz for an input pressure of 0.5 MPa over a time interval of 600 seconds.

3.2 Flow Sensing

For flow sensing, we developed a whispering gallery mode microlaser[11,12]. Silica microcapillaries were coated with a thin layer of erbium:ytterbium (Er:Yb) doped phosphate glass wire drawn from a bulk piece of material. A CO_2 laser was used to melt the phosphate glass wire onto the silica capillary. The difference between the melting temperature of silica (1,500°C) compared to phosphate (500°C) allowed us to develop this coating technique. The fabrication method led to a bottle-shaped laser resonator with an estimated Q-factor of $\sim 10^5$. The doped glass layer was excited at 980 nm via a tapered optical fiber (with a waist of a few μm). We observed lasing around 1535 nm. By passing air through the coated capillary, the excited WGMs were blue shifted due to the lower temperature of the gas, thereby enabling us to thermally tune the lasing modes. More than 70 GHz of tuning was achieved using this method. We connected the output of the capillary to a mass flow sensor and measured the mode frequency shift as a function of fluid flow rate and power in the 980 nm laser. We used the theory of hot wire anemometry[14] to fit the data.

4. CONCLUSION

We have presented two all-optical sensing methods that we have developed based on a tapered optical fiber and whispering gallery resonator system. Flow and pressure sensing have been achieved. We have used similar methods to develop a temperature sensor[2,3] with a microbubble resonator. One of the strengths of these techniques lies in the linear tunability of the whispering gallery modes as a function of the changes to the environment. For example, we have been able to demonstrate that internal aerostatic pressure tuning of a microbubble has several advantages over other methods of WGM tuning such as stress/strain and temperature tuning; therefore, it is a good alternative technique.

Though not discussed here, we have also been able to extend the functionality of microsphere resonators so that transient dispersive and dissipative sensing can be performed separately[10]. We have studied the dynamical mechanism behind cavity ring-up spectroscopy (CRUS) by determining the response to a Gaussian shaped input pulse as a function of laser detuning, rise time of the pulse, separation between the fiber and resonator, etc. Aside from the sensing applications, these systems have a range of other functionalities, not least we have developed a visible frequency comb[15] using a microbubble resonator.

REFERENCES

[1] Ward, J. M., Dhasmana, N. and Nic Chormaic, S., "Hollow core, whispering gallery resonator sensors," Eur. Phys. J. Spec. Top. 223, 1917–1935 (2014).

[2] Ward, J. M., Yang, Y. and Nic Chormaic S., "Highly sensitive temperature measurements with liquid-core microbubble resonators," IEEE Photon. Technol. Lett. 25, 2350–2353 (2013).

[3] Ward, J., Yang, Y. and Nic Chormaic, S., "Liquid core microbubble resonators for highly sensitive temperature sensing," Proc. SPIE 8960, Laser Resonators, Microresonators, and Beam Control XVI, 89601W (March 4, 2014).

[4] Yang, Y., Saurabh, S., Ward, J. M. and Nic Chormaic S., "High-Q, ultrathin-walled microbubble resonator for aerostatic pressure sensing," Opt. Express 24, 294 (2016).

[5] Sumetsky, M., Dulashko, Y. and Windeler, R. S., "Super free spectral range tunable optical microbubble resonator," Opt. Lett. 35, 1866–1868 (2010).

[6] Hanumegowda, N. M., Stica, C. J., Patel, B. C., White, I. and Fan, X., "Refractometric sensors based on microsphere resonators," Appl. Phys. Lett. 87, 201107 (2005).
[7] Vollmer, F., Arnold, S. and Keng, D., "Single virus detection from the reactive shift of a whispering-gallery mode," Proc. Natl. Acad. Sci. USA 105, 20701–20704 (2008).
[8] Hu, Y., Shao, L., Arnold, S., Liu, Y.-C., Ma, C.-Y. and Xiao, Y.-F., "Mode broadening induced by nanoparticles in an optical whispering-gallery microcavity," Phys. Rev. A 90, 043847 (2014).
[9] He, L., Ozdemir, S. K., Zhu, J., Kim, W. and Yang, L., "Detecting single viruses and nanoparticles using whispering gallery microlasers," Nat. Nanotechnol. 6, 428–432 (2011).
[10] Yang, Y., Madugani, R., Kasumie, S., Ward, J. M. and Nic Chormaic, S., "Cavity ring-up spectroscopy for dissipative and dispersive sensing in a whispering gallery mode resonator," Appl. Phys. B 122, 291 (2016).
[11] Ward, J. M., Yang, Y. and Nic Chormaic, S., "Flow sensor using a hollow whispering gallery mode microlaser," Proc. SPIE 9727, Laser Resonators, Microresonators, and Beam Control XVIII, 972718 (April 22, 2016).
[12] Ward, J. M., Yang, Y. and Nic Chormaic, S., "Glass-on-glass fabrication of bottle-shaped tunable micro-lasers and their applications," Sci. Rep. 6, 25152 (2016).
[13] Madugani, R., Yang, Y., Le V. H., Ward, J. M. and Nic Chormaic, S., "Linear laser tuning using a pressure-sensitive microbubble resonator," IEEE Photon. Technol. Lett. 28 1134-1137 (2016).
[14] Bruun H. H., [Hot-Wire Anemometry: Principles and Signal Analysis], Oxford Univ. Press, Oxford (1995).
[15] Yang, Y., Jiang, X., Kasumie, S., Zhao, G., Xu, L., Ward, J., Yang, L. and Nic Chormaic, S., "Four-wave mixing parametric oscillation and frequency comb generation at visible wavelengths in a silica microbubble resonator," Opt. Lett. 41, 5266-5269 (2016).