Photoinduced 3D optical cavities in chalcogenide glass

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A new approach to creating 3D optical cavities by exploiting the photosensitivity of chalcogenide glass is demonstrated, allowing monitoring during fabrication and dynamic tuning of optical properties.

Optical cavities, which confine light in an enclosed space for a prolonged time, can be used to purify the properties of light, enhance the interaction between light and matter, and explore the quantum nature of light. These features are critical for many important applications in sensors and analytical instrumentation, communications, and microwave photonics.

The geometries of optical cavities can be classified by the number of dimensions the optical path occupies. Zero-dimension optical cavities can be created by introducing a point defect in periodic structures, such as photonic crystals. One-dimensional cavities are typified by Fabry-Pérot resonators, in which light bounces back and forth between two mirrors. A good example of a 2D optical cavity is the so-called whispering gallery mode, in which light bounces along the circumference of a reflector with circular geometry. When it comes to 3D, things become more complicated for two reasons: first, the difficulty of maintaining a stable closed optical path in 3D; second, the difficulty of confining light in 3D while minimizing degradation.

One way of creating a high-quality 3D optical resonator is to exploit the property of light spiraling along the surface of a dielectric cylinder. For example, researchers have demonstrated bloated ‘bottle resonator’ cylinders that confine traveling spiral waves. Such designs offer better tunability than 2D cavities, and allow an appropriately chosen cavity mode to be tuned to an arbitrarily predetermined frequency. Although bottle resonators can be fabricated using a heating-and-puling method, precisely controlling geometries to produce complex profiles can be much more difficult, especially on microscopic scales. The heating process also prevents the cavity from being monitored in real time during fabrication.

Recently we discovered a new approach to creating 3D optical resonators. Our method makes no change to the shape of the dielectric cylinder, but instead introduces a tiny refractive index change (~10⁻³), causing total internal reflection of the spiral wave. Figure 1 shows how this works. In this illustration, the smooth refractive-index gradient shown at left can be approximated as a stack of material layers with different refractive indices. When a spiral wave enters from the higher-refractive-index layer, the angle of incidence increases as it propagates to a layer with lower refractive index, until it reaches the critical angle at a certain point and total internal reflection occurs. In reality, the index changes in a continuous fashion, but the underlying physics is the same. From Figure 1 we can see that a gentle index slope along the axis of a dielectric cylinder can serve as a total reflection mirror for the spiral waves, which can be used to make an optical cavity.

In our experiment (see Figure 2), an arsenic sulfide-based chalcogenide glass (ChG) fiber was used as the hosting material due to its unique photosensitive properties. Exposing the glass to green laser light induces a structural change that lowers the refractive index. To do this, we first tapered the ChG fiber down to a microfiber with diameter of 15 μm by heating and pulling. Then we shined a focused continuous wave green laser onto the microfiber. One side of the optical cavity is defined by a gentle index slope induced by the Gaussian profile of the green beam.

Figure 1. An index slope is a virtual total reflection mirror that can be used to control the transmission of spiral light. \( \Delta n \): Refractive index change. 

\( n_1 > n_2 > n_3 > n_4 > n_5 \)

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Figure 2. (a) Before laser exposure, spiral waves is not confined along the chalcogenide (ChG) microfiber. (b) A focused green continuous wave laser is used to modify the index profile along the fiber axis. (c) After exposure, the spiral wave is localized and a cavity is formed, characterized by resonance dips in the transmission spectrum. A sample spectrum of such resonance is shown in (d). SiO$_2$: Silica. A.U.: Arbitrary units. Q: Quality factor.

The cavity is excited and probed by touching it with a silica taper placed orthogonally to the microfiber. The measurement result indicates the quality factor $Q$ of our cavity ($\sim2 \times 10^5$), which is among the best of reported ChG cavities. Higher $Q$ indicates a lower rate of energy loss relative to the stored energy of the oscillator. A related publication from a different group showed that the same concept can be applied to silica glass by using surface expansion from CO$_2$ laser irradiation.

Our approach offers several advantages, including more control over cavity shaping, real-time monitoring during fabrication, and dynamic tuning. By exploiting the unique properties of ChG glass, our novel whispering-gallery-mode cavity architecture could be used to make efficient nonlinear optical devices and sensors for mid-IR wavelengths. The potential applications of this new approach are extensive. We have shown that a spiral wave can be controlled with a very small index change, induced either electronically or optically. Moreover, by manipulating the wave along the cylinder surface, other functionalities can be achieved. These include reconfigurable dispersion compensation, filtering, and optical delay on a microscopic scale. Next we will explore the nonlinear properties of the demonstrated cavities at mid-IR wavelengths for the application of low-threshold nonlinear signal processing and sensor fabrication.
References


