High Q Chalcogenide Photonic Crystal Nanobeam Cavities
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Abstract—We report high quality (Q) photonic crystal (PhC) nanobeam cavities in the chalcogenide glass Ge_{11.5}As_{24}Se_{64.5} near 1550 nm wavelength. By optimizing the structure of the PhC cavity, an ultra-high Q factor as large as \( 5 \times 10^6 \) is measured in the experiment. Such high-Q cavities in this strongly nonlinear material create an attractive platform for compact, ultrafast all-optical switches.

Index Terms—Integrated optics, photonic crystal, chalcogenide glasses, optical switches.

I. INTRODUCTION

PHOTONIC crystal (PhC) nanocavities with a high quality (Q) factor and low mode volume (V) are of great importance in various applications [1]–[2], such as ultralow energy switching and modulation [3]–[5], sensing [6], [7], and cavity quantum electrodynamics [8]–[10]. While the highest Q factors have been reported in 2D planar PhC cavities, nanobeam cavities (one-dimensional PhC cavities) have attracted much attention [11]–[13], because they can achieve large Q factors in addition to offering design flexibility and relatively simple fabrication, small size, and the ability to confine light in material systems with index contrasts too low to support 2D photonic bandgaps [14]–[17]. Additionally, such nano-beam cavities are easier to be connected or coupled with gratings, waveguides, and other nanophotonic resonators, such as microring resonator [18].

Bistable optical switching in a PhC resonant cavity is particularly attractive because they can be driven with an extremely low input power (scaled as \( V/Q^2 \)) for all-optical signal processing [5], [19]–[21]. The refractive index modulation via nonlinear optical effects such as thermo-optic (TO) effect [22], [23], carrier-induced effect [3]–[5], and Kerr effect [24]–[26] changes the cavity resonance. If the resonance change increases the effect of the index modulation, a positive feedback can be established resulting in optical bistability in a microcavity. The TO effect can be easily induced but suffer from the slow speed in the megahertz range, which is not useful for high-speed signal processing. On the other hand, carrier-induced effect, including two-photon absorption (TPA) and free-carrier dispersion, are always accompanied by high absorption loss, which significantly degrades the device transmittance. Kerr effect is carrier-free and is regarded as one of the most promising routes due to its instantaneous response and low optical loss. Utilizing its excellent features, optical switches and memories based on Kerr effect have been investigated both theoretically and experimentally [19], [25]–[27].

In spite of being a mature nonlinear photonics material, silicon shows significant TPA and free carrier absorption (FCA), which can degrade the performance of an optical switch at high-bit rates. Chalcogenide glasses (ChGs) are considered a promising material system instead of silicon to realize bistable switching as they afford low TPA and negligible FCA [28], as well as exhibit remarkable electrical and optical properties [29]. First, the linear absorption losses of ChGs are low over a wide wavelength range (up to \( \sim 20 \mu \text{m} \)) with the relatively high refractive index (\( n = 2 \sim 3 \)). Moreover, ChGs exhibit exceptionally high optical nonlinearity (Kerr, Raman and Brillouin coefficients) between two to three orders of magnitude greater than silica and comparable or superior to silicon [30]–[32], leading to numerous applications of all-optical signal processing, including optical interconnects [33], wavelength conversion [34], and supercontinuum generation [35], [36]. Several PhC cavities in chalcogenide glass have been demonstrated. White et al. [37] reported the first demonstration of 1D PhC nanocavities in chalcogenide glass Ge_{11.5}As_{24}Se_{64.5} with the Q factor of \( 2.2 \times 10^4 \). Gai et al. [38] designed and fabricated a 2-D photonic crystal heterostructure cavity in Ge_{11.5}As_{24}Se_{64.5} with a high intrinsic Q > \( 7.6 \times 10^5 \). Although these cavities exhibit good performance,
the As-containing chalcogenide glasses are toxic, which is not conductive to large-scale fabrication. We note that silicon nitride is another promising material for nonlinear optics, but the low index of the material (n~2) often poses challenges to be integrated with substrates with high index.

In this work, utilizing Ge$_{28}$Sb$_{12}$Se$_{60}$, one of the nontoxic ChGs, we present a design and fabrication of a high Q nanobeam cavity, which consists of a series of periodically arranged elliptical holes. In previous ChG photonics studies, the ternary and nontoxic ChG such as Ge–Sb–Se and Ge-Sb-S have attracted less attention than the As-containing and binary ChG such as As$_2$S$_3$ and As$_2$Se$_3$. This is mainly because the composition deviation of ternary films prepared by thermal evaporation is relatively large, which is not conductive to nonlinear photonics application. In recent years, people have made great progress in ternary ChG film preparation. For example, Chen et al. [39] successfully deposited Ge$_{28}$Sb$_{12}$Se$_{60}$ thin films with compositions close to the glassy target on glass slides at room temperature by thermal evaporation. Compared with As$_2$S$_3$ glass, which has been a major workhorse for all-optical devices to date [40], Ge$_{28}$Sb$_{12}$Se$_{60}$ has a higher linear refractive index (~2.8 compared with ~2.3 for As$_2$S$_3$) which leads to better mode confinement. By optimizing the size of elliptical holes, an ultra-high Q factor as large as 5 x 10$^6$ is predicted by simulation, and up to 1 x 10$^7$ is measured in experiment. Thanks to the high Q factor, high nonlinear coefficients and small mode-volume (V ~ 1.2(λ/n)$^3$), the reported ChGs nanobeam cavity shows great potential to demonstrate low-power, ultrafast switching, and optical signal processing.

II. DESIGN AND ANALYSIS

The structure based on the Ge$_{28}$Sb$_{12}$Se$_{60}$ platform is a dielectric mode elliptical-hole 1D PhC cavity, which includes a 300 nm thick Ge$_{28}$Sb$_{12}$Se$_{60}$ device layer and a 2 μm thick buried silicon dioxide layer. The refractive index of the Ge$_{28}$Sb$_{12}$Se$_{60}$ and silica buffer layer are 2.83 and 1.44, respectively, at a wavelength of 1550 nm. The upper cladding is set to be air. Figure 1(a) presents the schematic of the chalcogenide PhC nanobeam cavity, consisting of a 1D array of elliptical holes. From the top view of the cavity (Fig. 1(b)), the radius of the horizontal and the vertical axis of each elliptical cell are $R_x$ and $R_y$, respectively. To minimize scattering loss in the propagation direction x, we keep the period a, i.e., the transverse (x-axis) distance between the elliptical holes, constant to ensure optical phase matching between adjacent unit cells. To achieve a preferred Gaussian field profile, Quan et al. proposed an efficient method by introducing a linearly increased attenuation of the electromagnetic field from the center holes to the edge holes of the PhC cavity [11], [41]. Here, the radius of the vertical axis of the elliptical holes are modulated from $R_y(0)$ in the center to $R_y(n_{max})$ on the each sides parabolically: $R_y(n) = R_y(0) + \left(\frac{n}{n_{max}}-1\right) \times \left[R_y(n_{max}) - R_y(0)\right]$, n increases from 1 to $n_{max}$. Three-dimensional finite-difference-time-domain (3D-FDTD) method is used to simulate the photonic band structure, and finite-element-methods (FEMs) are used to simulate the field distribution of the PhC cavity with patterned elliptical holes. Figures 1(c) and 1(d) show the electric field distribution of the PhC cavity, from the top (xy-plane) and the side (yz-plane), respectively. We find that the fundamental TE mode of the cavity is a dielectric mode in which the optical field dominantly is located inside the high index chalcogenide region. In simulations, there are 25 elliptical unit cells in the taper region on each side of the PhC cavity, and only part of the cells is shown in the figure. Figure 1(e) shows the TE band diagrams of the PhC cavity, which are calculated from series band structure simulations with Bloch boundary conditions. The red curve shows the band diagram of $R_y(0) = 280$ nm (the vertical axis radius of the center ellipse hole), while the blue one indicates the band diagram of $R_y(n_{max}) = 100$ nm (the vertical axis radius of the edge elliptical hole). The resonance frequency of the cavity mode (the dot and dashed line in Fig. 1(e)) is slightly lower than the dielectric band edge of the elliptical cell with $R_y(0) = 280$ nm, which is consistent with the perturbation theory described by Quan and Loncar [41]. To keep the resonant wavelength of the cavity near 1550 nm, the period is chosen as a = 440 nm, and the waveguide width is chosen as W = 720 nm.

From the above optimization and analysis, the geometric parameters of the PhC nanobeam cavity are summarized to be: a = 440 nm, W = 720 nm, $R_y(0) = 280$ nm, $R_y(n_{max}) = 100$ nm, $R_x = 160$ nm, and $N_{mirror} = 25$ on each side. With these parameters, most of the electric field of resonant mode is confined in the high index chalcogenide region between
the elliptical holes of the PhC cavity. Further simulations by the finite element method show that the cavity mode exhibits a radiation-limited optical $Q$ as high as $5 \times 10^6$, with an effective mode volume as small as $\sim 1.2(\lambda/n)^3$ (defined by $V = \int dV|E|^2/(\epsilon|E|^2)_{\text{max}}$, where $E$ is the electric field and $\epsilon$ is the permittivity). The resonant wavelength of the fundamental mode used for the cavities is 1531.7 nm.

III. FABRICATION AND CHARACTERIZATION

The designed ChGs PhC nanobeam cavity was fabricated on a chalcogenide glass platform using the following process as illustrated in Fig. 2. First, a 300 nm thick film of Ge$_{28}$Sb$_{12}$Se$_{60}$ glass was thermally deposited onto a 2-$\mu$m oxidized silicon wafer as a substrate. Then a negative tone electron beam resist (MA-N 2403) was spin-coated onto the Ge$_{28}$Sb$_{12}$Se$_{60}$ wafer at 4000 rpm, and the thickness of the MA-N 2403 film was 330 nm. Electron beam lithography (Raith Eline Plus) is used to define patterns at an acceleration voltage of 30 KV, and then developed in MA-D 525 solution. Inductively coupled plasma etching using a gas mixture of CHF$_3$ and CF$_4$ was then used to transfer the PhC pattern into the chalcogenide film. To remove the remaining resist, we first put the sample into the ICP etcher, and bombard it with the gas mixture CHF$_3$/AR/O$_2$ for 20s, then shake it with a 1-Methyl-2-pyrrolidone on a 70 °C shaker for 3 minutes, and finally rinsed in DI water.

Figures 3(a) and 3(b) show the scanning electron micrographs (SEMs) of the fabricated cavity and the zoom in view of the elliptical holes at the end of the PhC cavity, respectively. The minimum feature size of the cavity is $\sim 80$ nm, which shows clearly well-defined and uniform elliptical holes and an accurately patterned lattice structure. To characterize the performance of the device, we measured the transmission spectrum of resonators using a vertical fiber coupling setup. Grating couplers were fabricated at each input and output port for chip-fiber coupling and polarization selectivity, as shown in Fig. 3(c). The TE polarization grating coupler was designed with a fixed duty cycle of 70%, a period of 920 nm, and in Fig. 3(c). The TE polarization grating coupler was designed for chip-fiber coupling and polarization selectivity, as shown in Fig. 3(c). The TE polarization grating coupler was designed for chip-fiber coupling and polarization selectivity, as shown in Fig. 3(c).

Figure 3(d) presents the transmission spectrum of the device normalized by the peak resonance transmission. The cavity has a fundamental mode resonance at 1514.1 nm. The full width at half maximum (FWHM) for the Lorentz fit of the measured result is $\sim 126$ pm, which indicates a high $Q$ factor of $\sim 1.2 \times 10^4$. The extinction ratio is larger than 15 dB. The degradation of the $Q$ factor compared with the design is mainly due to the sidewall scattering loss and the inhomogeneity of the shape of the holes caused by the dry etching process. Further improvement of $Q$ factor may be achieved by optimizing the fabrication processes. In addition, we found that the PhC cavity supports higher-order resonance modes, and the higher-order mode can be well separated from the fundamental mode. The $Q$ value of the higher-order mode is significantly smaller than the fundamental one.

IV. CONCLUSION

We have demonstrated the design and fabrication of a high $Q$ PhC nanobeam cavity on Ge$_{28}$Sb$_{12}$Se$_{60}$ platform. Benefitting from the Gaussian-shaped field profile within the cavity, an optimized $Q$ factor of $\sim 5 \times 10^6$ in simulations and $\sim 1.2 \times 10^4$ in the experiment has been achieved. Furthermore, the total size of the nanobeam is only $24 \times 0.72 \mu m^2$. The availability of such compact, high $Q$ and high nonlinear nanobeam cavity makes them excellent candidates to low-power, ultrafast switching, and optical signal processing.

REFERENCES
