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ABSTRACT
We propose and demonstrate an approach for 10 kHz to 34 MHz ultrasound detection based on a dual-core As$_2$Se$_3$-PMMA taper. We fabricate dual-core As$_2$Se$_3$-PMMA tapers with a Young’s modulus 24 times smaller than that of silica fibers, which enhances the acoustic response. Dual-core As$_2$Se$_3$-PMMA fiber tapers show high sensitivities to both shear and longitudinal waves due to the dual-core structure, low Young’s modulus, submicrometer dimension of the core, and the high-contrast interference pattern by the even and odd modes. A dual-core As$_2$Se$_3$-PMMA taper with a core diameter of 0.6 μm detects acoustic waves in the frequency range from 10 kHz to 34 MHz, which are excited by three piezoelectric transducers with optimal operating frequencies of 100 kHz, 3.65 MHz, and 6.8 MHz, respectively.

I. INTRODUCTION
Ultrasound detection plays a significant role in many applications, such as structural health monitoring and biomedical imaging. Structural health monitoring is required by the industry to identify the initial damage, monitor its subsequent progress, and predict the remaining life of a structure.1 The importance of ultrasound detection has been increasing in clinical applications. Ultrasonic waves can propagate into organs without losing their coherence, which have great potential for noninvasive imaging.2-3

In a plate-like structure, a piezoelectric transducer (PZT) generates lamb waves that are elastic waves which cause particle motion to move in the plane containing the direction of wave propagation and the plate normal. Lamb waves can be conceived as a system of longitudinal and shear waves propagating across and along the plate.4-5 Longitudinal waves are waves in which the displacement of the medium is in the same direction as, or the opposite direction to, the direction of propagation of the wave. The shear waves move as transverse waves, so medium motion is perpendicular to the direction of wave propagation.

Tapered dual-core As$_2$Se$_3$-PMMA fibers composed of two As$_2$Se$_3$ cores in the center and a surrounding polymethyl methacrylate (PMMA) cladding are promising platforms for sensing applications. The PMMA cladding provides high flexibility, robustness, and lower Young’s modulus that enhances sensitivity for strain, stress, and acoustic wave detection.6 Simultaneous temperature and strain measurements have been achieved based on dual-core As$_2$Se$_3$-PMMA tapers. Variation of the taper temperature or strain changes the length and the refractive index of tapers, shifting the trough wavelengths in the transmission spectrum.

In this paper, a 1 cm-long dual-core As$_2$Se$_3$-PMMA fiber with an As$_2$Se$_3$ core diameter of 0.6 μm and a PMMA cladding diameter of 34 μm is fabricated and used for ultrasound detection. The principle for ultrasound detection based on a dual-core As$_2$Se$_3$-PMMA taper is introduced, which shows that the dual-core structure enables high-sensitivity detection for shear waves and the low Young’s modulus enhances the sensitivity for longitudinal waves. Three PZTs with optimal operating frequencies of 100 kHz, 3.65 MHz, and 6.8 MHz are measured experimentally in order to test the frequency response of the fabricated dual-core As$_2$Se$_3$-PMMA ultrasound sensor.

II. PRINCIPLE OF ULTRASOUND DETECTION BASED ON A DUAL-CORE As$_2$Se$_3$-PMMA TAPER

Figure 1 presents the principle of ultrasound detection in which the wavelength of a tunable laser source is adjusted on the spectral slope of the transmission spectrum of a dual-core taper. The ultrasound signal changes the taper length and the refractive index of the dual-core taper leading to a variation of the transmitted power...
of a laser that is aligned at a quadrature point of the transmission spectrum such that the power variation is proportional to the time-varying ultrasound wave amplitude. A photo-detector (PD) converts power variation at the output of the dual-core taper into an electrical signal which is measured using an oscilloscope (OSC). The AC components of the signal observed on the oscilloscope are expressed by Eq. (1),

$$V_S = \Delta \lambda G R D P_{power}^\text{in} = R D_{out} P_{power}^\text{out},$$

where $V_S$ is the detected AC signal voltage, $\Delta \lambda$ is the wavelength shift of the transmission spectrum caused by the ultrasound signal in a dual-core taper, $G$ is the maximum slope in the transmission spectrum of the dual-core taper, $R_D$ is the photodetector’s response factor, $P_{power}^\text{in}$ is the input laser power, and $P_{power}^\text{out} = \Delta \lambda G P_{power}^\text{in}$ is the output power from the dual-core taper. A large wavelength shift caused by the ultrasound signal and a steep spectral slope increase the sensitivity of the system.

A PZT acoustic generator is not possible to be viewed as a point source, and the dual-core taper experiences both shear and longitudinal waves whose effects cannot be differentiated. The propagation direction of ultrasound waves by PZTs is affected by the size and shape of PZTs, the size, shape, and materials of the substrate plate. Both the shear and longitudinal waves can propagate perpendicular to and along or partially along the microwire.

**A. Effect of shear waves**

As illustrated in Fig. 2(a), the interaction length of the acoustic waves with a dual-core taper is determined by the incident angle $\theta$. As shown in Fig. 2(b), within the interaction length range, the acoustic waves periodically bend the dual-core fiber, which changes the refractive index distribution in the dual-core fiber, and hence, the coupling of the even and odd modes is changed accordingly.

When light is launched into core-1 of the dual-core fiber, the input light is split equally between the even and odd modes. These two modes superpose along the dual-core fiber to form an antisymmetric periodic spatial power distribution as illustrated in Fig. 2(a), where $\Lambda$ is the spatial period of intensity oscillations and is equal to 6.5 $\mu\text{m}$ in the dual-core $\text{As}_2\text{Se}_3$-PMMA fiber with an $\text{As}_2\text{Se}_3$ core diameter of 0.6 $\mu\text{m}$ and a PMMA cladding of 34 $\mu\text{m}$. The small value of the spatial period of 6.5 $\mu\text{m}$ enables high-frequency ultrasound detection. As shown in Fig. 2(b), acoustic shear waves periodically bend dual-core tapers and change the refractive index distribution leading to the change of the coupling of the even and odd modes. The normalized output power is given by

$$P_{power}^\text{out} = \frac{1}{4} \sin^2 (L C) \cos (\omega_t),$$

where $L$ is the length of the dual-core taper, $C$ is the acousto-optic coupling coefficient, and $\omega_t$ is the angular frequency of the acoustic waves.

The dual-core structure enables high sensitive ultrasound detection for shear waves. Furthermore, due to the impedance mismatch between the aluminum plate, air, and PMMA cladding, surface acoustic waves can be supported and mixed with the shear waves to form further spatial deformations. The amplitude of surface acoustic waves depends on the thickness of the substrate plate, the acoustic frequency, and PZT acoustic generators.

**B. Effect of longitudinal waves**

As illustrated in Fig. 3, the longitudinal waves propagating with an angle $\theta$ to the dual-core taper induce a stress along the propagation direction of the longitudinal waves, which modulates the length and the refractive index.

The stress induced by PZTs is assumed to be a sinusoidal form, which is expressed by Eq. (2),

$$P_{stress}(t) = P_{0}^\text{stress} \cos \left( \frac{2\pi}{\lambda_z} z - \omega_t t \right),$$

where $P_{0}^\text{stress}$ is the ultrasonic stress amplitude, $\lambda_z$ is the ultrasonic wavelength, and $\omega_t$ is its angular frequency.
The wavelength shift of a quadrature point in the transmission spectrum of the dual-core taper depends on the stress induced length change of the fiber and the refractive index change in the fiber.

The length change is described by elasticity theory. When a dual-core taper is stretched or compressed, the wavelength of the quadrature point in the transmission spectrum shifts accordingly. Due to the geometric effect, a particular point in the interaction range between the longitudinal acoustic waves and the dual-core microwire shown in Fig. 3 with a position \( z \) along the z-axis is translated into a new position \( z' \), which is expressed by Eq. (6):

\[
z' = z + \int_0^z \alpha \xi d\xi.
\]

Then, the fiber length change within the interaction range between the longitudinal acoustic waves and the dual-core microwire induced by mechanical contribution along the z-axis under the ultrasound wave action is expressed as

\[
\Delta L_w = -\alpha p_0 \frac{\lambda_0}{2\pi} \left( \sin \left( \frac{2\pi}{\lambda_0} L_w - \omega t \right) + \sin \left( \omega t \right) \right),
\]

where \( \alpha = (1 - 2\nu)/E \).

The refractive index change is described by the strain-optic effect. Light propagating in the z-axis sees a change in the index of

\[
\Delta n = \frac{1}{2} n^2 \beta p_0 \frac{\lambda_0}{E} \left( 1 - 2\nu \right) (2P_{12} + P_{11}).
\]

Substituting Eq. (2) into Eq. (8), the refractive index change is given by

\[
\Delta n = \frac{1}{2} \beta p_0 \frac{\lambda_0}{E} \left( 1 - 2\nu \right) (2P_{12} + P_{11}).
\]

where \( \beta = n^2 (2P_{12} + P_{11}) \), \( n \) is the refractive index of the material, and \( p_{ij} \) is the elasto-optic coefficients with \( i = 1 \) and \( j = 1 \) or 2.

Table I gives the typical values of the refractive index \( n \), elasto-optic coefficients \( P_{11} \) and \( P_{12} \), Poisson’s ratio \( \nu \), and the Young’s modulus \( E \) of silica fibers, As2Se3, and PMMA material. The values of \( \alpha \) and \( \alpha + \beta \) are calculated, which shows that As2Se3 cores and PMMA cladding have a larger modulation depth in the fiber length and refractive index than silica fibers.

### C. Effect of \( R_D \)

The photodetector’s response factor, \( R_D \), is affected by the noise performance of photodetectors. In optoelectronic systems for ultrasound detection, there are three principal sources of noise: shot noise, thermal noise, and the flicker noise (1/f noise) that are negligible in the ultrasound frequency range. The power spectral density of the shot noise is proportional to the average optical power, while the

| Material     | \( n \)     | \( P_{11} \) | \( P_{12} \) | \( \nu \) | \( E \) (GPa) | \( \alpha \) | \( \alpha + \beta \) |
|--------------|------------|------------|------------|--------|-------------|---------|-------------|
| Silica fiber | 1.456      | 0.121^12   | 0.27^12    | 0.17^12 | 73^15       | 0.009   | 0.018       |
| As2Se3      | 2.81       | 0.314^14   | 0.266^14   | 0.292^15 | 16.3^15     | 0.026   | 0.479       |
| PMMA        | 1.35       | 0.30^19    | 0.297^14   | 0.37^16 | 3^16        | 0.087   | 0.191       |

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thermal noise is independent of the optical power. The shot noise governs the ultrasound sensitivity since the optical power into the photodetector is usually larger than ~20 dBm where the shot noise dominates the noise of the photodetector. The power into the photodetector (the power output from the dual-core taper) is expressed as $P_{\text{power}} = \Delta \lambda \Delta \beta L P_{\text{in}}$ in Eq. (1), and the selection of the slope in the transmission spectrum of the dual-core taper and the input laser power $P_{\text{in}}$ affects the power into the photodetector changing the noise floor and impacting the signal to noise ratio (SNR) of the detected ultrasound signal.

### III. EXPERIMENT SETUP AND RESULTS

To receive broadband ultrasound frequencies, the size of ultrasound sensors should be sufficiently small compared with the wavelength of the ultrasound signal; otherwise, the sensors become barely sensitive to the ultrasonic waves due to the spatial averaging.

A 1 cm-long dual-core $\text{As}_2\text{Se}_3$–PMMA fiber with an $\text{As}_2\text{Se}_3$ core diameter of 0.6 $\mu$m and a PMMA cladding of 34 $\mu$m is fabricated and used for the ultrasound detection, as described in Refs. 18 and 19. Figure 4 presents the measured transmission spectrum of the fabricated taper showing a periodic variation of intensity with the wavelength. The transmission power is given by $P = P_0 \cos(\Delta \beta L)$, where $\Delta \beta$ is the difference of propagation constants between the even and odd modes, $L$ is the fiber length, and the wavelength dependent transmission arises from the wavelength dependence of $\Delta \beta$. The maximum variation of intensity with the wavelength occurs at the quadrature points of the transmission spectrum.

Figure 5 presents the schematic of the setup for ultrasound detection based on a tapered dual-core $\text{As}_2\text{Se}_3$–PMMA fiber. An external-cavity laser (ECL) is used as a laser source with an output power of 0 dBm whose wavelength is tuned by a thermal control to the quadrature point of the spectral slope of the transmission spectrum of the dual-core taper. The light from the ECL passes a tunable attenuator (TA) and a linear polarizer (LP) followed by a polarization controller (PC) that is utilized to align the polarization of the laser with one of the principal axes of the dual-core fiber. The light passes through the dual-core fiber and a photo-detector (PD) is used to detect the output optical signal. In order to cover the ultrasound frequency range from 10 kHz to 34 MHz, three PZTs glued to an aluminum plate with dimensions of 320 mm × 100 mm × 7 mm are utilized as ultrasound generators. Optimal operating frequencies of PZT-1, PZT-2, and PZT-3 are 100 kHz, 3.65 MHz, and 6.8 MHz, respectively.

First, PZT-1 is driven by an arbitrary function generator (AFG) with a sinusoidal electric signal to generate ultrasound waves. The dual-core fiber is placed 2 cm away from PZT-1 and ultrasound signals impact the dual-core fiber to induce a temporal variation in the transmission power. An example of the temporal response of the detected acoustic signal at a frequency of 100 kHz is shown in Fig. 6(a) when the driving voltage is 10 V, and a zoomed-in view of the measured signal is presented in Fig. 6(b) showing a periodic sinusoidal signal at the frequency of 100 kHz. The signal to noise ratio (SNR) of the detected ultrasound signal is obtained by calculating the difference between the power of the signal at the frequency of 100 kHz and the averaged power of the neighboring frequency components after performing the fast Fourier transform (FFT) on the time-domain signals as shown in Fig. 6(c), and the SNR of the detected 100 kHz ultrasound signal is ~70 dB.

A commercial PZT sensor (1-channel microphone conditioning amplifier) is placed close to the dual-core fiber to calibrate the ultrasound vibrations from PZT-1. The effective frequency range of the PZT sensor is between 1 kHz and 200 kHz. Figure 7(a) presents the acoustic stress calibrated by the commercial PZT sensor when the driving voltage from the AFG on PZT-1 changes from 0.1 V to 10 V at 100 kHz. Figures 7(b) and 7(c) present the amplitude and spectral response of the sensor for a 100 kHz ultrasonic wave.
SNR of the detected signals of the proposed dual-core taper sensor and the commercial PZT sensor as a function of the acoustic stress at 100 kHz, respectively. Figure 7(d) presents the SNR values of the fabricated dual-core taper sensor and the commercial PZT acoustic sensor in the frequency range from 10 kHz to 200 kHz. The maximum frequency of the fabricated dual-core sensor is 3.4 MHz as shown in Fig. 7(e).

PZT-2 and PZT-3 are used for ultrasound generation in the frequency range between 100 kHz and 34 MHz when the driving voltage is 10 V. Figure 8(a) presents the SNR of PZT-2 as a function of ultrasound frequency, which shows high SNRs for a frequency range from 100 kHz to 34 MHz. Figure 8(b) presents the SNR of PZT-3 as a function of ultrasound frequency within a frequency range from 100 kHz to 32.5 MHz. The SNR of the detected signal is determined by the performance of ultrasound generators (PZTs) and the frequency response of the receiver (the fabricated dual-core fiber sensor). The SNRs in Figs. 8(a) and 8(b) are different due to the different ultrasound performance of PZT-2 and PZT-3.

IV. DISCUSSION

The material property of the dual-core $\text{As}_x\text{Se}_y$-PMMA taper is superior to that of silica-fiber based sensors for ultrasound detection. First, when an acoustic wave is imposed on a dual-core taper, due to the acousto-optic effect, the acoustic-wave induced strains give rise to the large variations in the refractive index and the optical path length, shifting the transmission spectrum correspondingly. Second, PMMA is a promising material for ultrasound propagation, because its impedance is similar to that of water, which makes the dual-core $\text{As}_x\text{Se}_y$-PMMA tapers a good candidate for hydrophone applications. Finally, the PMMA cladding provides high mechanical robustness for use in practical applications.

The size of the ultrasound sensors is required to be sufficiently small to detect high-frequency ultrasound waves. The core diameter of the proposed dual-core taper ultrasound sensor is only 0.6 μm enabling it for high-frequency ultrasound detection. In addition, the dual-core structure enhances the sensitivity for shear waves that changes the coupling coefficient of two fundamental modes. The high-contrast interference pattern in the transmission spectrum also contributes to the ultrasound detection by inducing a large spectral slope at the quadrature point of the transmission spectrum.

The ultrasound sensors based on dual-core $\text{As}_x\text{Se}_y$-PMMA tapers can be made insensitive to temperature variations. An approach for a temperature-insensitive strain sensor has been
reported using a dual-core As$_2$Se$_3$-PMMA taper with an As$_2$Se$_3$ core diameter of 0.61 μm and a PMMA cladding diameter of 34.4 μm. Thermally-induced forces on the As$_2$Se$_3$ cores by the PMMA cladding are adjusted by tapering the As$_2$Se$_3$-PMMA fiber such that the effect of variations of the difference between effective refractive-indices of the even and odd modes on the fiber transmission spectrum counterbalances the effect of fiber elongation when the temperature changes. The temperature-insensitivity property of the dual-core As$_2$Se$_3$-PMMA taper opens the path for the implementation of reliable ultrasound sensors and devices with immunity to temperature fluctuations over a broad frequency range from 10 kHz to 34 MHz. The detected upper-frequency response of the proposed dual-core As$_2$Se$_3$-PMMA taper sensor is limited by the availability of commercial high-frequency ultrasound generators.

V. CONCLUSION

Ultrasound detection based on a dual-core As$_2$Se$_3$-PMMA taper is demonstrated. A taper with a core diameter of 0.6 μm detects acoustic waves in the frequency range from 10 kHz to 34 MHz. The small size, dual-core structure and low Young’s modulus of the proposed sensor are favorable for the high frequency and high sensitivity ultrasound detection. Future work is being carried out to achieve ultrasound sensors with a higher frequency response and insensitive to temperature variations.

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