Optical vibration sensor fabricated by femtosecond laser micromachining

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We fabricated an optical vibration sensor using a high-repetition rate femtosecond laser oscillator. The sensor consists of a single straight waveguide written across a series of three pieces of glass. The central piece is mounted on a suspended beam to make it sensitive to mechanical vibration, acceleration, or external forces. Displacement of the central piece is detected by measuring the change in optical transmission through the waveguide. The resulting sensor is small, simple, and requires no alignment. The sensor has a linear response over the frequency range 20 Hz–2 kHz, can detect accelerations as small as $0.01\ \mathrm{m/s^2}$, and is nearly temperature independent. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2008362]

Vibration measurements play an important role in many fields, including shock wave detection, acoustic signal recording, real-time structural assessment, and microelectromechanical system (MEMS) positioning.[1–3] Because electric vibration sensors are prone to electromagnetic field interference, several designs for optical sensors have been proposed. Examples include fiber Bragg gratings, a gap between two fibers, and photonic crystal waveguides.[1,2,4–10] However, fiber Bragg gratings are affected by temperature, strain and pressure, and require additional equipment to observe the vibration-induced frequency shifts; photonic crystal waveguides require complex manufacturing techniques; and sensors using two fibers are delicate. In this letter we report the fabrication of an integrated waveguide-based vibration sensor using a femtosecond laser oscillator. The sensor converts vibrations into easily detectable intensity changes, is easy to manufacture and assemble, is sturdy, and can be made very small.

Femtosecond lasers can induce a permanent refractive index change inside various transparent materials, enabling the writing of embedded optical waveguides. This technique has been used to fabricate a number of photonic devices such as optical couplers, diffraction gratings, and interferometers.[11–17] Oscillator-only micromachining[15] enables high-speed writing of round waveguides and avoids any self-focusing effects because the peak power is one order of magnitude below the critical power for self-focusing.[18] The absence of self-focusing ensures that the waveguide is created at the geometrical focus of the microscope objective, facilitating the writing of a connected waveguide across multiple pieces of glass.

Figure 1 shows a schematic diagram of the sensor, which consists of an optically connected waveguide across three pieces of soda-lime glass. The central piece is mounted on a flexible suspended beam, making it sensitive to external vibrations and accelerations, while the two adjacent pieces are secured to a substrate. Single-mode optical fibers are connected to the ends of the micromachined waveguide using a UV-cured epoxy. Displacement of the central glass piece with respect to the adjacent ones causes a transmission loss through the sensor.

The waveguide is written across the three pieces of glass by translating the focus of a Ti:sapphire laser through the assembly, as illustrated in Fig. 1. The laser generates a 25-MHz train of 20-nJ, 55-fs pulses, which are focused into the sample with a 1.4-NA objective lens.[15] Index-matching oil between the objective and the surface of the glass compensates for any vertical offset between the three pieces of glass. The oil also fills the 3–10 μm gaps between the pieces of glass, eliminating any discontinuities in index. In spite of the continuity in index, the resulting waveguide is interrupted over a distance of approximately 20 μm across each gap, as shown in Fig. 2. The asymmetry in the ends of the waveguide suggests that differences in thermal properties between the oil and the soda-lime glass cause the focus to deteriorate during translation across the gap. Although the waveguide is physically discontinuous at the gaps, it is optically connected: at wavelengths of 632.8 and 1550 nm we observe single-mode transmission with a waveguiding loss of approximately 2.0 dB.

We determined the transmission losses through the sensor by coupling light from a 1.55-μm laser diode into the input fiber and measuring the output of the sensor with an InGaAs photodiode. In equilibrium, the fixed overall loss across the entire sensor is less than 10 dB. Mechanical displacement of the central piece of glass causes additional loss through the sensor. Figure 3 shows the dependence of this

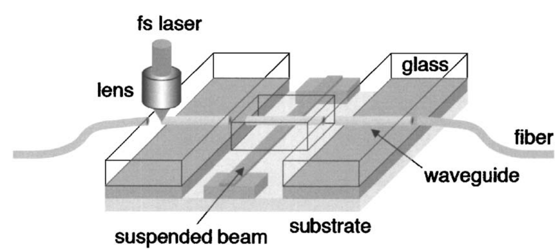

FIG. 1. Vibration sensor consisting of a waveguide written across three pieces of glass. The suspended beam supporting the central piece of glass is made of borosilicate glass; the rest of the sensor is made of soda-lime glass. The sample is translated at 20 mm/s with respect to the microscope objective.

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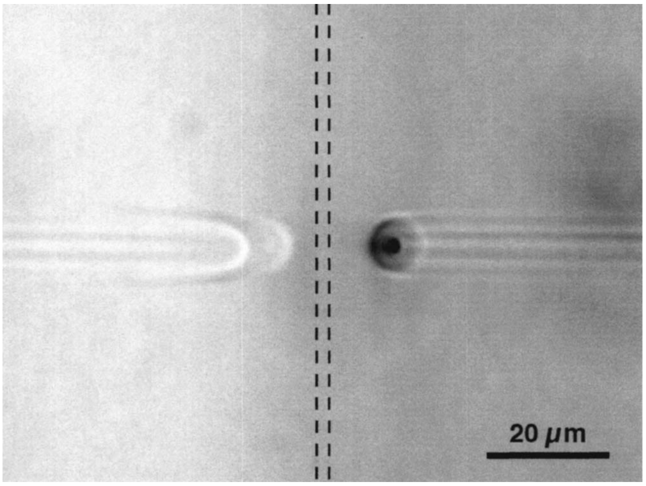

FIG. 2. Transmission optical microscope image of the embedded waveguide near the 3-μm wide gap (dashed lines) between two pieces of glass. The gap is not visible because it is filled with index-matching oil. Although the waveguide is interrupted over a distance of 20 μm, it is optically continuous.

additional loss on the displacement of the central glass piece. Assuming the waveguides have the same Gaussian mode field diameter ω and a lateral offset δ between their cores, the coupling efficiency is $\eta = \exp(-2\delta^2/\omega^2)$. The dashed line in Fig. 3 represents a fit of this efficiency to the data for offsets smaller than 10 μm. The discrepancy between the data and the fit at larger offsets can be attributed to the non-Gaussian refractive index profile of the waveguide.[17]

To calibrate the sensitivity of the sensor we need to determine the spring constant of the suspended beam. To this end we measured the displacement loss caused by placing weights (0.4–9.0 g) on the central piece of glass. Using the data in Fig. 3 to convert displacement loss to offset, we can then relate applied force to offset and determine the spring constant; for a sensor with a $20 \times 2 \times 0.1$ mm^3 borosilicate glass beam we obtain a spring constant of 1.2×10^4 Nm^{-1}.

After calibration we measured the sensor's temporal response to external vibrations by mounting it on the rim of a computer-controlled speaker. Figure 4 shows the power spectrum of the sensor output at a fixed 100-Hz harmonic-oscillation frequency of the speaker. The power spectrum containing higher-order harmonics are due to the anharmonic relation between loss and offset shown in Fig. 3. However,

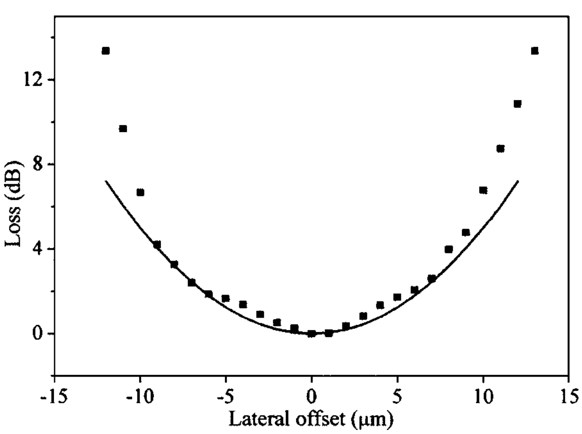

FIG. 3. Waveguide loss dependence on lateral offset. Circles: experimental data; dashed line: fit to theory.

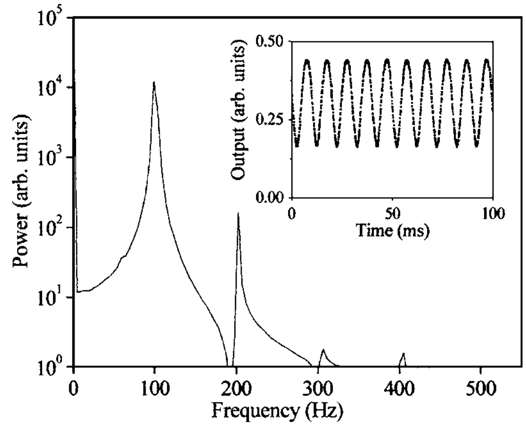

FIG. 4. Power spectrum of sensor response to a 100-Hz acoustic signal. The power spectrum is obtained by taking the Fourier transform of the time domain response (inset).

the amplitude of these harmonics is negligible compared to the amplitude at the fundamental 100-Hz oscillation frequency.

Figure 5 shows the sensor's frequency response, obtained by varying the speaker frequency but keeping the oscillation amplitude fixed. The frequency response shows a strong resonant frequency around 200 Hz. Away from the resonant frequency, the response is reduced due to damping in the suspended beam. The frequency response can be tuned in two ways: by attaching a weight to the central piece of glass and by varying the material or dimensions of the suspended beam to change its spring constant. The response shown in Fig. 5 was obtained with a 2.5-g weight attached to the central piece of glass. Regardless of damping effects, the sensor shows a linear relation between input and output for the entire range of tested frequencies, from 20 Hz to 2 kHz.

The sensor can also be used as an accelerometer. Because the sensor is only sensitive to vertical displacements, accelerations along orthogonal directions are decoupled. Given the small dimensions of the sensor, multiple sensors can be combined in a single device to sense acceleration along all directions. We measured the acceleration response of the sensor using a linear translation stage and found a minimum sensitivity of 0.01 m/s^2 using a 6-g weight fastened to the central piece of glass.

The sensor's temperature dependence was determined by heating it from 293 to 343 K. This rise in temperature causes

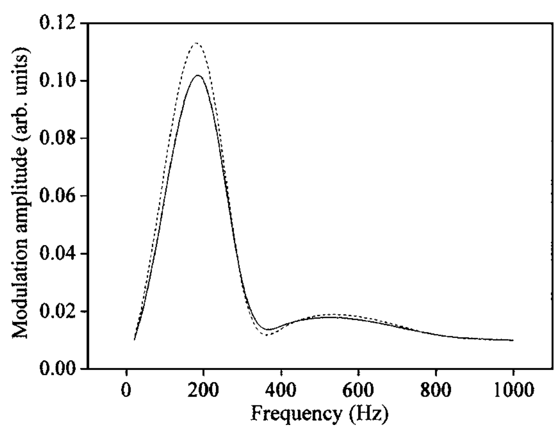

FIG. 5. Frequency response of the sensor at 293 K (solid line) and 343 K (dotted line).

a maximum change of 10% in the frequency response, as shown in Fig. 5. We attribute this small change to a temperature dependence in the bending modulus of the suspended beam. The materials used in our prototype can be changed to minimize these effects. Because vibrations and accelerations are detected by measuring relative changes in transmission, the temperature-induced changes in the frequency response do not affect the linearity, range, or sensitivity of the sensor.

In summary, we demonstrated a novel vibration sensor fabricated using femtosecond laser micromachining. Our technique allows for the fabrication of a waveguide that is optically connected across several pieces of glass in a single pass. The sensor is suited for all-optical sensing of displacements, vibrations, and accelerations with minimum temperature dependence and immunity to external electromagnetic fields. This technology provides an alternative sensor for use where standard electric vibration sensors and other optical sensors are not suitable.

[1] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, J. Lightwave Technol. **15**, 1442 (1997).
[2] Golnabi Hossein, Rev. Sci. Instrum. **70**, 2875 (1999).
[3] Y. J. Rao, Meas. Sci. Technol. **8**, 355 (1997).
[4] T. A. Berkoff and A. D. Kersey, IEEE Photon. Technol. Lett. **8**, 1677 (1996).
[5] M. LeBlanc, S. Y. Huang, M. Ohn, R. M. Measures, A. Guemes, and A. Othonos, Opt. Lett. **21**, 1405 (1996).
[6] E. Ollier, IEEE J. Sel. Top. Quantum Electron. **8**, 155 (2002).
[7] N. Takahashi, K. Yoshimura, and S. Takahashi, Jpn. J. Appl. Phys., Part 1 **39**, 3134 (2000).
[8] A. M. Vengsarkar, J. R. Pedrazzani, J. B. Judkins, P. J. Bergano, and C. R. Davidson, Opt. Lett. **21**, 336 (1996).
[9] Y. N. Zhu, P. Shum, C. Lu, M. B. Lacquet, P. L. Swart, A. A. Chtcherbakov, and S. J. Spammer, Opt. Express **11**, 1918 (2003).
[10] O. Levy, B. Z. Steinberg, M. Nathan, and A. Boag, Appl. Phys. Lett. **86**, 104102 (2005).
[11] K. M. Davis, K. Miura, N. Sugimoto, and K. Hirao, Opt. Lett. **21**, 1729 (1996).
[12] E. N. Glezer, M. Milosavljevic, L. Huang, R. J. Finlay, T. H. Her, J. P. Callan, and E. Mazur, Opt. Lett. **21**, 2023 (1996).
[13] K. Minoshima, A. M. Kowalevicz, I. Hartl, E. P. Ippen, and J. G. Fujimoto, Opt. Lett. **26**, 1516 (2001).
[14] S. Nolte, M. Will, J. Burghoff, and A. Tuennermann, Appl. Phys. A **A77**, 109 (2003).
[15] C. B. Schaffer, A. Brodeur, J. F. Garcia, and E. Mazur, Opt. Lett. **26**, 93 (2001).
[16] L. Sudrie, M. Franco, B. Prade, and A. Mysyrowicz, Opt. Commun. **171**, 279 (1999).
[17] A. M. Streltsov and N. F. Borrelli, Opt. Lett. **26**, 42 (2001).
[18] J. H. Marburger, Prog. Quantum Electron. **4**, 35 (1975).