Waveguide Wiring Between Multiple Pieces of Glass Using Femtosecond Lasers for Optical Sensor Applications

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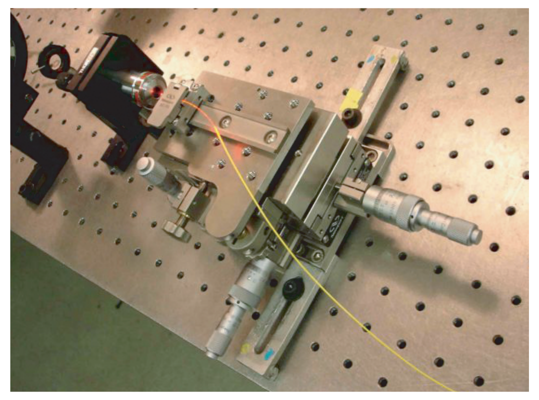
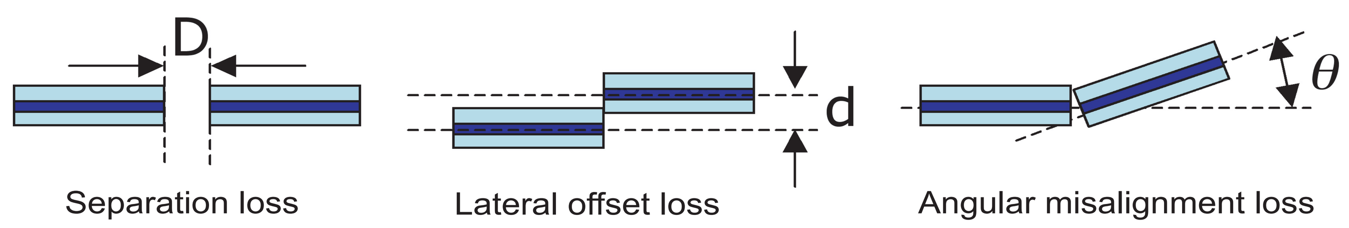
Introduction

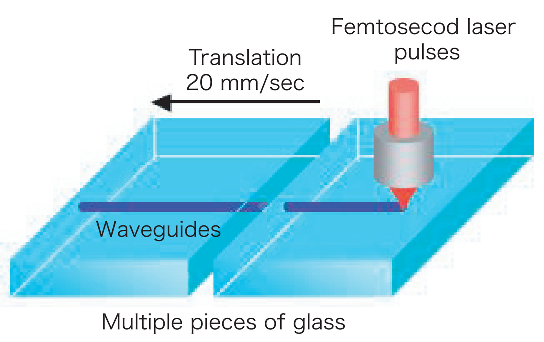
Precise alignment is a limiting requirement for waveguide coupling raising the cost of photonic device fabrication. Although active and passive alignment techniques exist, femtosecond laser writing provides the analog of "circuit printing".
We propose a novel and simple technique to fabricate connected waveguides by use of femtosecond lasers.



Coupling light to waveguides



main loss sources of connected waveguides



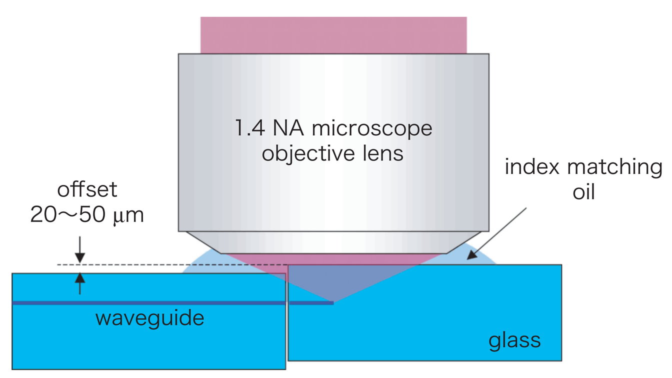
Writing waveguides

We employ a long cavity 25 MHz, 55 fs, 30 nJ, 800 nm Ti:Sapphire femtosecond laser oscillator and an oil immersion 1.4 NA objective lens for waveguide writing*. Oscillator-only technique allows for high-speed writing of waveguides (20 mm/s) with index changes on the same order of a standard optical fiber. We demonstrate the practicality of this technique fabricating waveguide-based vibration sensors.

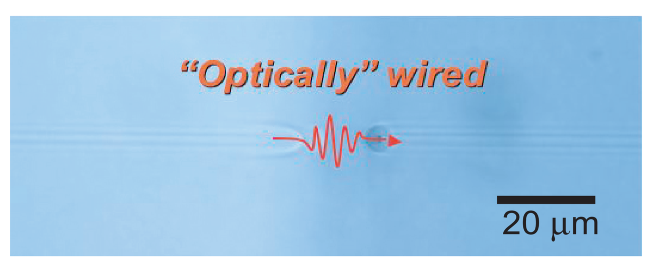
*Chris B. Schaffer, Andre Brodeur, Jose F. Garcia, Eric Mazur, Opt. Lett. **26**, 93 (2001).

Waveguide wiring

Wiring across multiple pieces of glass starts with polishing and assembling the pieces. The use of index matching oil (from the high N.A. objective) provides minimal optical path changes; waveguides are written even in the presence of offsets between glass pieces.
The use of oil reduces the accuracy of the glass assembly process to the point manual assembly is possible. Since the structure is all polished and assembled prior to laser exposure, no post treatment is necessary.

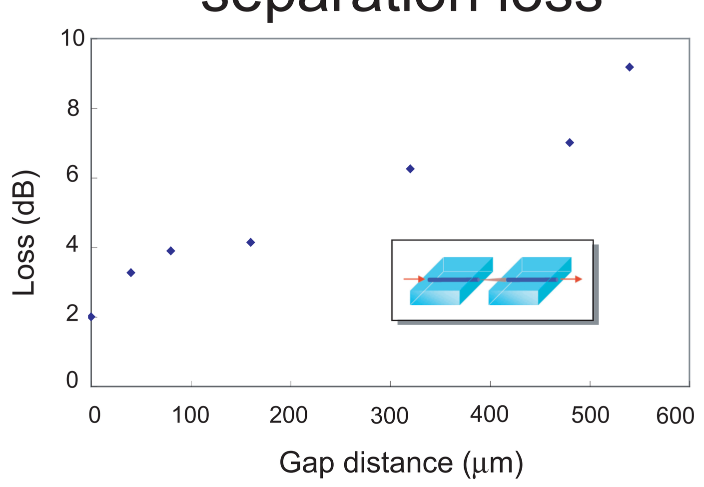


light focusing

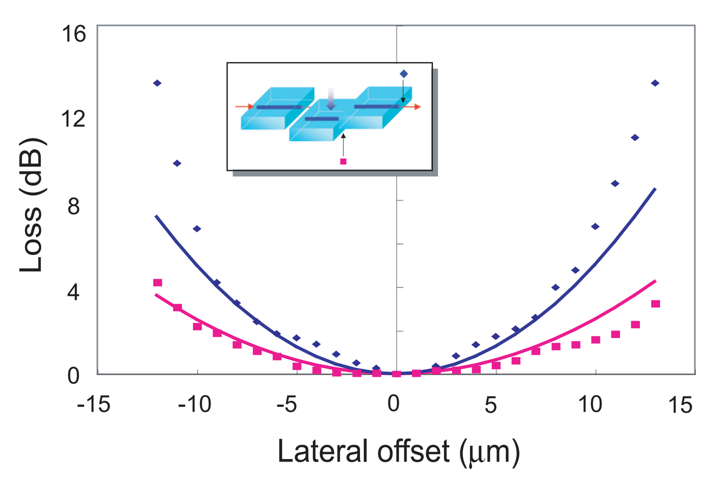


microscope picture of wired waveguides

separation loss



lateral offset loss



Separation loss (left) and lateral offset loss (right) of the wired waveguides. The solid lines in the right figure are theoretical curves.

Light is still coupled from the left waveguide to the right one even if the gap distance is over 500 μm.

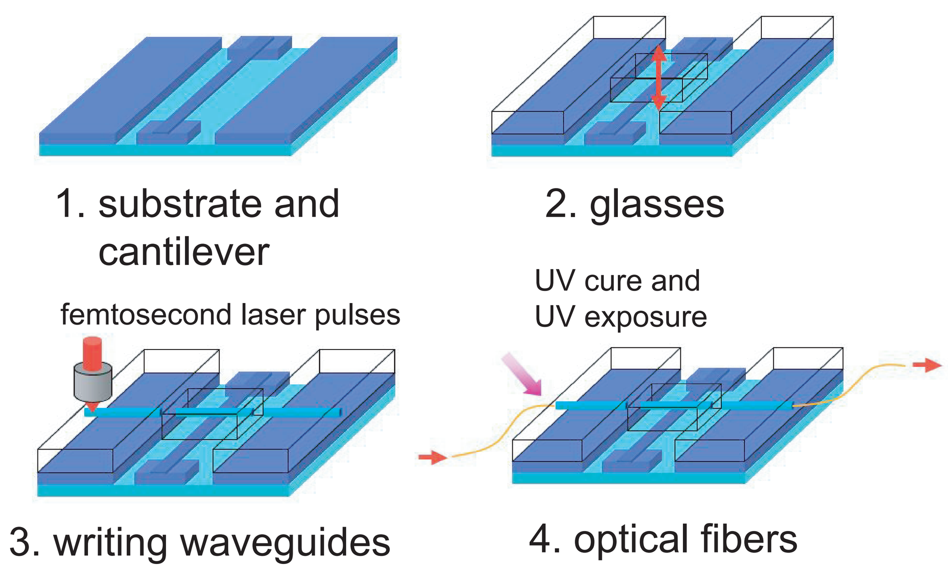
The lateral offset loss is very sensitive to the displacements. The solid lines represent theoretical curves calculated by

$$\eta = \frac{\left|\int_{-\infty}^{\infty} E_1(x)E_2^*(x)dx\right|^2}{\left[\int_{-\infty}^{\infty}|E_1(x)|^2dx\right]\left[\int_{-\infty}^{\infty}|E_2(x)|^2dx\right]}$$

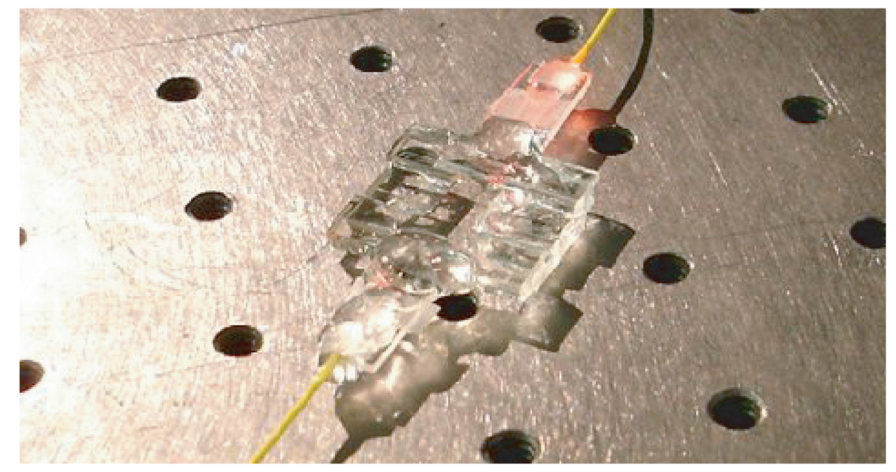
where E_1 and E_2 represent electric fields in each waveguide. The experimental result matches well with the theoretical curve around the center of the curve, but deviates from the theoretical curve at larger offsets. This discrepancy is due to the non-Gaussian refractive index profile of the fabricated waveguides.

Waveguide-based vibration sensor

Vibration measurements of buildings, vehicles, airplanes and machines provide real time assessment of structural aging and damages that occur in long-term uses. To this end, optical sensors have many advantages over conventional electrical sensors in terms of electrically passive operation, high sensitivity and large bandwidth, small dimensions and immunity from electromagnetic field interferences vibration sensor using the waveguide wiring technique.



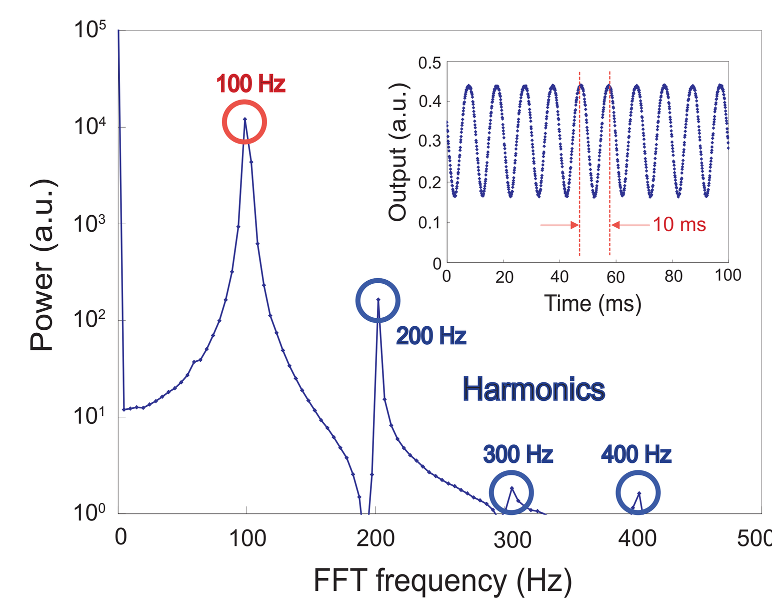
flow chart of the sensor fabrication



Although fiber Bragg grating sensors have been extensively studied so far, they remain sensitive to both strain and temperature, making it difficult to separate the effects.
This shortcoming is overcome with the waveguide-based vibration sensor developed by use of the waveguide wiring technique.

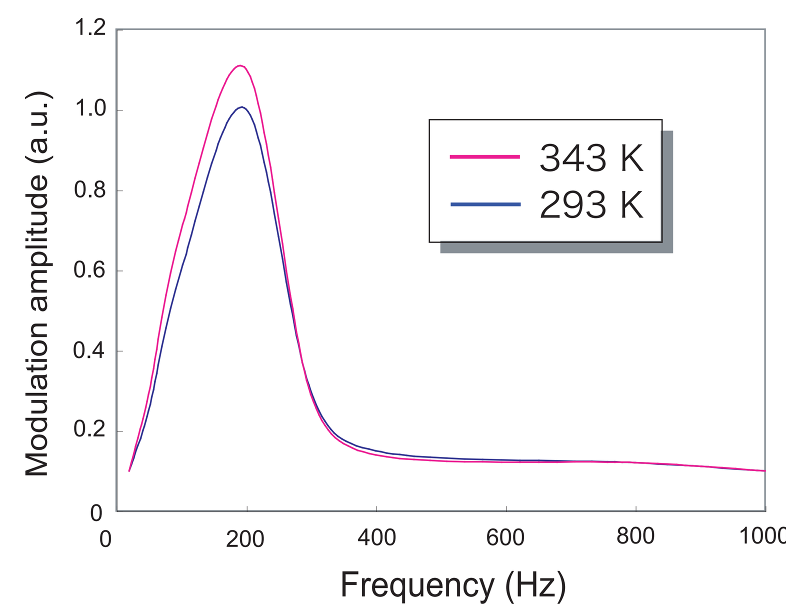
Vibration measurements

We have characterized the temporal and frequency response of the sensor. Once the sensor was attached to the rim of a computer-controlled speaker, light from a 1.55 μm laser diode was coupled to the sensor though an external fiber.
The sensor response was detected at the output side by an InGaAs photodiode.



Temporal (inset) and frequency response of the sensor to 100 Hz sound wave.

Frequency response at higher harmonics are present and come from the nonlinear relationship between the offset and the loss.



Temperature dependence of the sensor on the modulation amplitude as a function of input frequency.

We examined temperature dependence of the sensors on modulation amplitude between 293 K and 343 K using a heater attached to the substrate of the sensors. The temperature dependence is negligible overcoming the serious limitations encountered in fiber Bragg grating sensors.

The sensor design used for vibration also serves for measurements of accelerations. We have used a linear translation stage to test the sensor. Preliminary results show a sensitivity for accelerations as low as 0.01 m/s^2.

Summary

We propose a novel technique to write connected waveguides by use of femtosecond lasers. Our technique allows for the fabrication of a waveguide that is connected across several pieces of glass in one pass of the laser. Using this technique, we have fabricated a waveguide-based vibration sensor. The sensor is suited for all-optical sensing of vibration and acceleration quantities. This novel technology can be used even under the environment that regular electric vibration sensors and fiber Bragg grating sensors cannot be used.