# Biconical Fiber Taper Sensors

Khanh Quoc Kieu and Masud Mansuripur

***Abstract*—We present several simple sensitive fiber-optics-based sensors that utilize a biconical fiber taper. A displacement sensor with 100-nm accuracy, a temperature monitor with sensitivity $\Delta T \sim 1$ °C, and a refractive-index sensor capable of measuring $\Delta n \sim 1.42 \times 10^{-5}$ are demonstrated using tapers made from a standard single-mode fiber.**

***Index Terms*—Displacement sensor, fiber taper, refractive index sensor, temperature sensor.**

## I. INTRODUCTION

FIBER-OPTIC sensors have found increasing applications in different technological fields [1]. Various types of fiber sensors have been proposed and demonstrated [2]–[4]. Fiber-taper-based sensors are among the simplest of such devices, as they do not require expensive and complex fabrication procedures. In contrast, fiber Bragg grating (FBG) sensors, for example, require expensive phase-masks. Recently, strain, high temperature, and refractive index sensing using tapered microstructured optical fiber has been reported [5]–[7]. However, the authors used tapered microstructured fiber which is expensive and difficult to work with in term of getting low loss splicing with standard optical fiber. In this letter, we show that better performance (in terms of loss, spectral response and working range) of sensing devices can be obtained with standard single-mode optical fiber tapers.

Tapering a single-mode optical fiber involves reducing the cladding diameter (along with the core) by heating and pulling the fiber's ends. The heat source can be a gas burner, a focused $CO_2$ laser beam, or an electronic arc formed between a pair of electrodes (in a fusion splicer, for example). The result of tapering is the so-called fiber taper, which consists of three contiguous parts: 1) a conical segment where the diameter of the fiber gradually decreases; 2) a relatively long taper waist section where the diameter of the fiber is small and uniform; 3) a second conical segment where the taper ends, with its waist merging into the single-mode fiber again. Depending on the pulling conditions (pulling speed, length of the heated zone, pulling temperature, etc.), one can fabricate biconical tapers with different shapes and properties.

Fiber tapers may be divided into two distinct categories: adiabatic and nonadiabatic. It has been shown that nonadiabatic biconic fiber tapers can be made such that coupling occurs primarily between the fundamental mode of the unpulled fiber and the first two modes of the taper waveguide $(\mathrm{HE}_{11}, \mathrm{HE}_{12})$, where the light propagates at the air–cladding interface of the taper's waist region. (Due to the large difference between the refractive indexes of air and glass, the taper normally supports more than one mode.) The result of back and forth coupling between the single mode of the fiber and the two (or more) modes of the taper is oscillations in the spectral response of the taper, that is, transmission is high for certain wavelengths and low for others. (Typically, transmission versus wavelength shows periodic behavior [8], [9].)

The aforementioned effects can be readily explained by looking at the coupling process in detail. First, the light propagates in the fundamental mode of the single-mode fiber. At the taper region, this mode is coupled into several modes (mostly the first two modes) of the multimode taper waveguide. The light then travels down the taper and is coupled back into the single-mode fiber again at the exit end of the taper. The efficiency of this last coupling is dependent on the relative phase of the participating modes. When there are only two modes, the relative phase $\Delta\phi = \Delta\beta \cdot l$, where $\Delta\beta$ is the difference in propagation constants of the two modes, and $l$ is the interaction length along the taper. Now, if by some means, $\Delta\beta$ or $l$ change, the spectral response of the taper will change (or shift) correspondingly. For instance, if the taper is stretched, the phase difference will change due to a change of $l$, and the spectral response will shift accordingly. Alternatively, if the refractive index of the taper's surrounding environment changes, $\Delta\beta$ will change and, again, the spectral response will shift. It is thus obvious that one can build displacement sensors or refractive index sensors based on nonadiabatic biconical fiber tapers. In what follows, we shall investigate the response of biconical tapers to changes in taper length (caused by stretching), temperature, and refractive index.

## II. FABRICATION PROCEDURE AND EXPERIMENTAL RESULTS

We make our fiber taper by heating (using a butane flame burner) and stretching a piece of single-mode fiber (SMF 28, Corning), where the protective coating has been removed. The flame is about 5 mm wide and is fixed during the pulling process. The fiber is pulled only from one side, with controllable speed and pulling distance. Before heating/stretching the fiber, we couple the light from a narrow linewidth tunable laser (Agilent 81682A) into one end of the fiber, then monitor the fiber's transmission using a power meter (Newport 1835-C) during the heating/pulling process. Strong periodic oscillations in transmission through the fiber taper were observed during the heating/pulling process [10]. Typically, the loss of our fiber tapers is less than 15%. After the tapering process, we measure the spectral response of the fiber taper using the narrow-linewidth tunable laser. The response is nearly sinusoidal (when microstructured fiber was used, the spectral response of the tapers was a lot more irregular due to excitation of more than two modes in the taper region [5]–[7]), indicating that primarily two modes are responsible for the observed behavior. Fig. 1 shows a typical spectral response of our fiber

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Manuscript received June 21, 2006; revised August 10, 2006.

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Color versions of Figs. 1, 2, 4, and 5 are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2006.884742

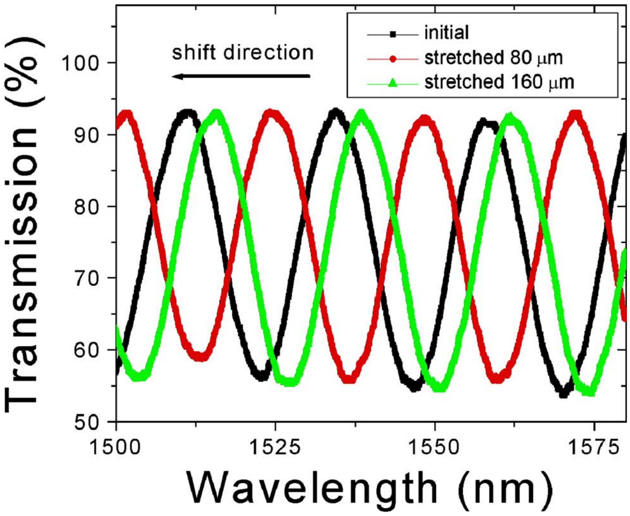


Fig. 1. Spectral response of a biconic fiber taper and its shift upon stretching. Taper's length ∼12 mm, taper's diameter ∼8 $\mu$m.

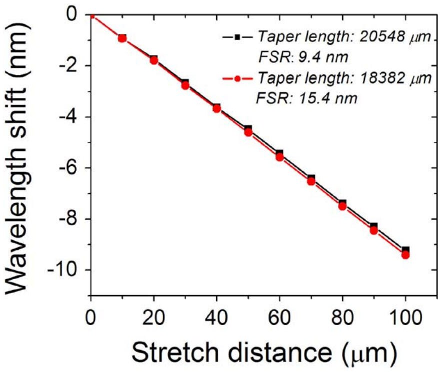
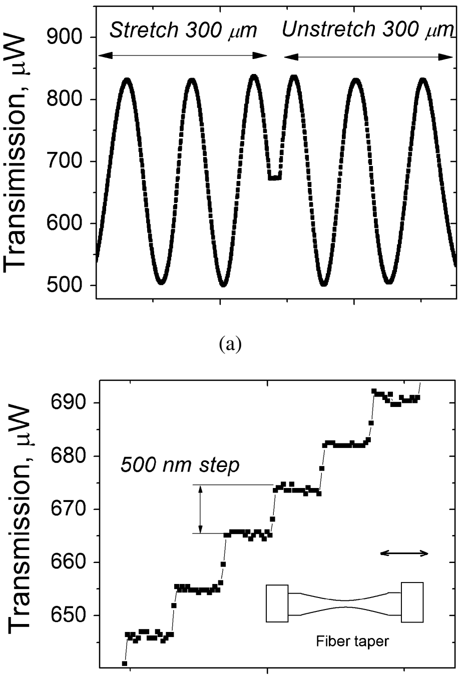


Fig. 2. Wavelength shift observed for two different tapers versus the stretch distance. The length and the FSR of the depicted tapers are ($L = 20.548$ mm, FSR $= 9.4$ nm) and ($L = 18.382$ mm, FSR $= 15.4$ nm).

tapers. Furthermore, if the taper is stretched (without heating) the spectral response is blue-shifted (see Fig. 1).

Fig. 2 shows the wavelength shift of two different tapers versus the stretch distance. The free spectral range (FSR) of the taper is defined as the measured period of the spectral response (i.e., transmissivity versus wavelength). Normally, longer tapers possess smaller FSR when all other pulling conditions are kept constant (e.g., pulling speed, temperature). In Fig. 1, we observe that the wavelength shift does *not* depend on the taper length (or the FSR). For all tapers, the shift in wavelength is ∼95 pm per micron of stretch. The spectral shift is reversible over a wide range of stretch (at least 700 $\mu$m for tapers longer than 10 mm). Longer tapers have a wider working range, which could be up to several millimeters in some cases. With our tunable laser, we could detect wavelength shifts up to 10 pm, which corresponds to a sensitivity of ∼100 nm for our displacement sensor. It is worth noticing that the strain (relative displacement) sensitivity of our sensors can be improved simply by increasing the distance between the points of attachment to the substrate. This is different from displacement/strain sensors based on FBGs, because, in the latter case, the strain is distributed along the fiber between the fixed points. The taper diameter (typically about 10 $\mu$m) is small in comparison to the initial fiber's diameter, so most of the strain stretch is concentrated in the taper region.



(a)

(b)

Fig. 3. (a) Transmission variation versus the stretch/unstretch distance through an $L = 16.269$ mm, FSR $= 12$ nm fiber taper. (b) Close-up of the transmission signal through a fiber taper when stretching/unstretching is applied in $\Delta L = 500$ nm steps.

Our biconical fiber tapers have a periodic response in the $\lambda$∼1550 nm region. Therefore, one can build low-cost displacement sensors using a simple edge detection technique, thus eliminating the need for expensive tunable lasers or optical spectrum analyzers to detect the wavelength shift. In this case, the laser wavelength is fixed; if a stretch (or displacement) is applied to the taper, its spectral response will shift correspondingly, resulting in a change in the transmission of the light through the taper. Fig. 3(a) and (b) shows the change in transmission of the $\lambda = 1550$ nm laser light when the taper is stretched a total of 300 $\mu$m in 0.5-$\mu$m steps and then unstretched. Periodic response and good reversibility are observed. From this data, the estimated sensitivity of the device is $\Delta L$∼100 nm. Higher sensitivities may be achievable with tapers that have a smaller FSR, since the wavelength shift will remain unchanged for identical displacements.

Next we investigated the temperature response of our fiber tapers. The tapers were glued at both ends to a glass substrate. Before affixing to the substrate, the tapers were unstretched by ∼150 $\mu$m to eliminate possible effects of thermal expansion; this ensures that only the thermal response (change in material's refractive index) of the tapers is being monitored. From these experiments, we learned that the operation of the tapers is insensitive to bending as well. We observed a linear dependence of the wavelength shift on temperature; longer tapers had a larger slope. In the particular case presented in Fig. 4, the slope of the wavelength shift was about 10 pm/°C for the $L = 20.548$ mm taper, while it was ∼6.7 pm/°C for the $L = 18.382$ mm taper. The dependence of the slope of the wavelength shift on taper

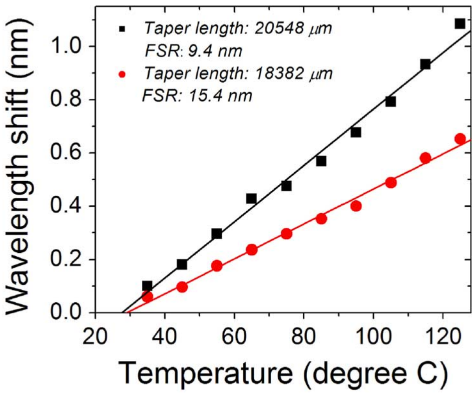


Fig. 4. Wavelength shift versus the ambient temperature. The length and the FSR of the depicted tapers are ($L = 20.548$ mm, FSR $= 9.4$ nm) and ($L = 18.382$ mm, FSR $= 15.4$ nm).

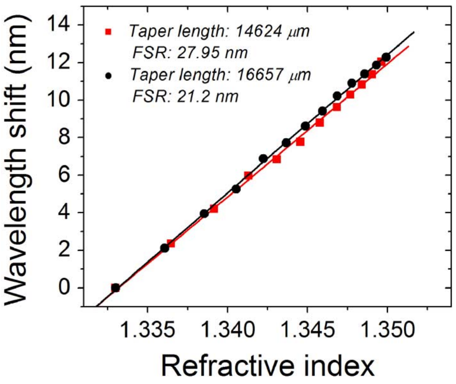


Fig. 5. Wavelength shift of the transmitted beam as a function of the refractive index of the liquid surrounding the fiber taper.

length can be explained by the fact that for the same change in the material's refractive index, longer taper gives larger optical path length difference. It is worth mentioning that our temperature sensor works from room temperature while the temperature sensor described in [5] can only measure temperature higher than 200 °C.

Note also that the wavelength is red-shifted with the increasing temperature. Therefore, for displacement/strain sensors using biconic tapers, the temperature dependence can be easily compensated by using a substrate with an appropriate thermal expansion coefficient. The wavelength shift caused by the temperature variation is then canceled out by the corresponding shift due to the thermal expansion of the substrate. This is one of the advantages of our displacement/strain sensor, considering that FBG-based sensors suffer from strong temperature dependences, and special techniques are needed to separate the useful strain response from the spurious thermal response [1].

Our fiber tapers can be used as temperature sensors, although the sensitivity is not great; with the 10-pm resolution of wavelength shift detection in our setup, we have a sensitivity of only ~1 °C. However, one can use the large stretch response of fiber tapers to measure temperature with high sensitivity in an alternative configuration. The idea is to fix the taper to a substrate having a large thermal expansion coefficient (e.g., aluminum). The substrate will expand/shrink with varying temperature, resulting in stretching/unstretching of the taper.

To measure the sensitivity of our fiber tapers to the refractive index of the surrounding environment, we transferred the taper from the pulling setup to a Teflon chamber filled with water $(n = 1.333)$. The refractive index of the liquid inside the Teflon chamber was then changed by adding KCl solution (20% KCl concentration by weight). The refractive index of this solution is a known linear function of KCl concentration [11].

Fig. 5 shows the measured wavelength shift as a function of the refractive index of the surrounding environment for two different tapers. A linear dependence of the wavelength shift versus the refractive index is observed. For all the tapers studied, the shift was nearly constant, at ~12 nm when the index of the liquid changed from 1.333 to 1.350. With a 10-pm resolution for the wavelength shift detection, the refractive index sensitivity of our device is $\Delta n \sim 1.42 \times 10^{-5}$. This corresponds to a KCl concentration detection sensitivity in the order of 0.01%. Our refractive-index sensors have high sensitivity in the 1.333 region, which is important for measuring the concentration of various water-based solutions. Also notice that a simple edge-detection technique can be used (as in the case of the displacement fiber taper sensors described above), thus simple and practical devices are possible.

## III. CONCLUSION

We have proposed and built several fiber-optic sensors based on standard telecom single-mode fiber tapers. Despite the simplicity of the concept, high-sensitivity measurements of displacement, temperature, and refractive index were demonstrated. These sensors should be fairly easy to mass-produce owing to their simplicity and compatibility with inexpensive demodulation schemes.

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