Subnanometer Resolution Single Mode *Elastica* Fiber Optic Displacement Sensors

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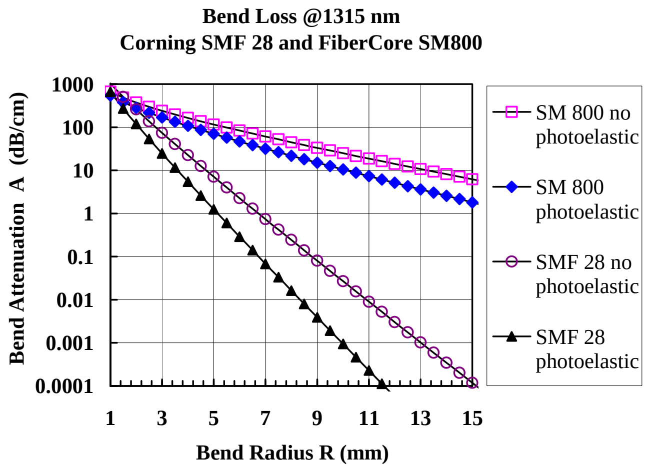
Abstract: A 10 mm *Elastica* with dT/dx = -7.9x10^{-3}/μm and sensitivity of 0.28 nm with SNR of 2.1 at 25.4 Hz is presented. The 10 μWatt shot noise limited SNR of 2 sensitivity is 0.016 nm/$\sqrt{Hz}$.

OCIS codes: (060.2370) Fiber Optics Sensors; (060.2300) Fiber Measurements; (060.2270) Fiber Characterization

1. Introduction

Elastica fiber optic sensors are fiber optic intensity sensors that are based on the principle of nonlinear buckling of the fiber and the resulting precisely controllable bending loss [1]. Due to their several unique properties [2], extremely low cost, large strain sensing range, high resolution, low thermal apparent strain, extremely low force constant, flexibility in mounting and deployment configurations, and enhanced reflection sensitivity, they have proved invaluable for high temperature and harsh environment sensors [3], as well as numerous other structural monitoring applications [4]. *Elastica* fiber sensors have been implemented in both multimode and single mode fiber. In the present work we focus on single mode fiber *Elastica* due to the existence of a theoretical model for the transmission loss that is in good agreement with existing experimental results [4,5]. The modeling of multimode fiber *Elastica* is much more complex due to the lack of accurate expressions for the bend loss coefficients for the higher order modes, and the difficulty in characterizing the mode power distribution of highly multimode fibers.

Bending loss in ordinary single mode, step index fibers is extremely sensitive to the *V* number of the fiber. Shown in Fig. 1 is a plot of bend attenuation vs. bend radius for 2 different fibers corresponding to Corning SMF 28 and FiberCore SM 800 fiber, both operating at 1315 nm. The SM 800 fiber is designed to operate at 830 nm, and as a result of operating at a wavelength of 1315nm, has a very low *V* number of 1.43. As can be seen from the figure, the bend loss coefficient varies over more than 20 orders of magnitude for the different fibers and radii of curvature. The incredible sensitivity to bend radius and the fiber parameters results because the loss coefficient is an exponential as a result of optical tunneling through the effective index barrier created by the curved optical fiber [6]. Note that the correction to the bend loss due to the photoelastic effect is very large [7], since it helps to guide the mode around the bend, effectively increasing the radius of curvature by about 30% [8]. Figure 1 also shows the fiber parameters used for the theoretical calculations. Surprisingly, the Petermann 2 mode field diameter [9] using the exact LP_{01} mode field is nearly identical for the two fibers, despite their large differences in *V* and core diameter.



Fiber Parameters		SM 800	SMF 28
Core Diameter (μm)		5.00	8.00
Petermann 2 MFD (μm)		9.03	9.00
V @ 1315 nm		1.433	2.348
	NA	0.12	0.123
	nco	1.45167	1.45191
	Δ	3.434E-03	3.60E-03
	η	1.3074	1.3074
	λc (nm)	786	1284

Fig. 1 Bend Attenuation vs. Bend Radius for Corning SMF 28 and FiberCore SM800 single mode step index fibers at 1315 nm. Upper and lower curves for each fiber are calculated both without (upper) and with (lower) the photoelastic effect correction to the radius of curvature [6,7], where η is the photoelastic coefficient. Fiber parameters are derived from manufacturer's data. $NA = \sqrt{n_{co}^2 - n_{cl}^2}$.

2. *Elastica* transmission properties

Previous *Elastica* fiber sensors have been fabricated with Corning SMF 28 operating at 1315nm. [4,5] and in multimode [2] fiber (MMF) at 840 nm. The sensitivity of a 10 mm length MMF *Elastica* is $dT/dx = -3.325\text{x}10^{-4}/\mu\text{m}$. The slope sensitivity of *Elastica* fiber sensors is a strong function of the straight length, the best reported 5.1 mm MMF *Elastica* sensitivity is $dT/dx = -2.4\text{x}10^{-3}/\mu\text{m}$. Although these sensitivities are good, and adequate for many measurement situations, it was desired to see if it was possible to further improve the sensitivity of single mode *Elastica* and to measure their minimum detectable displacements.

Figure 1 suggests one way to increase the bend loss sensitivity of single mode fiber *Elastica* is to use single mode fiber with a lower *V* number. This can be done by using ordinary step index, single mode fiber that is designed for normal operation at a shorter wavelength, and operating it at a much longer wavelength, thus reducing the *V* number and significantly increasing the bend loss sensitivity. In the present case, we chose a fiber that was designed for operation at 830 nm ($V = 2.27$), and operated it at a wavelength of 1315nm ($V = 1.43$).

With such low *V* number fiber, one might wonder if the fiber core will even guide the mode, and if splice loss will be excessive due to mode field mismatch. As already pointed out, the exact Petermann 2 mode field radius is nearly identical for these two fibers, so one expects very low splice loss. A detailed calculation of the square of the overlap integral power transmission coefficient for the two exact LP_{01} mode fields for the fiber parameters shown in Fig. 1 gives a transmission of 0.975 or 0.11 dB loss. Thus low losses can be achieved in splices between these two fibers with very different core sizes and *V* numbers, which also serves to minimize excess light launched into the cladding. In our experimental setup, a 60 cm piece of SM 800 was spliced to 2 other 1.5 meter pieces of SMF 28, which were in turn spliced to 1.5 meter input and 3 meter output, connectorized SMF 28 cables. A total of 4 splices plus 2 FC/PC connectors gave a total loss 1.27 dB. The two splices between the SMF 28 and SM 800 fiber alone, if perfectly aligned, would account for only ~0.22 dB of the total splice and connector loss.

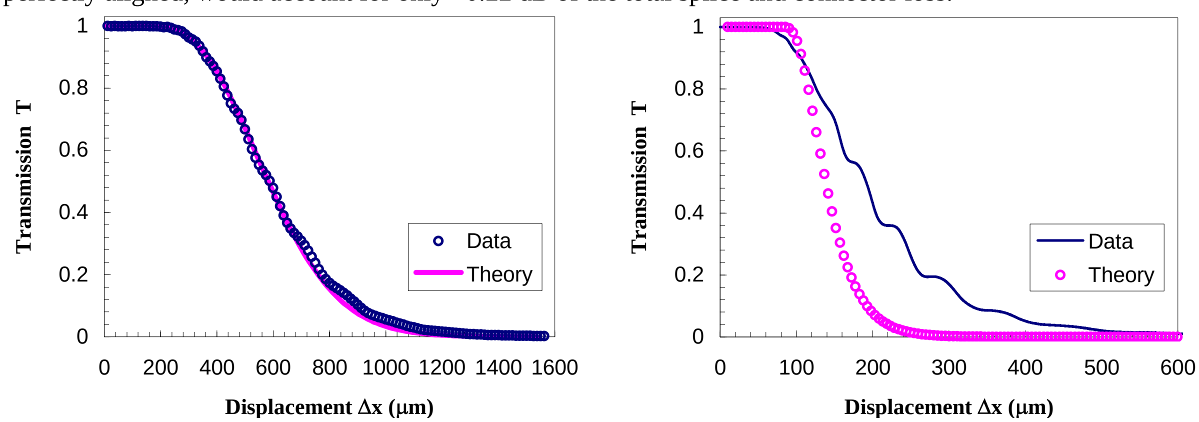


Fig. 2. Transmission vs. displacement for 10.21 mm SMF 28 *Elastica* (left) and 10.0 mm SM 800 *Elastica* (right).

Figure 2 shows excellent agreement of the theoretical adiabatic transmission loss model [4] with the measured data for a 10.21mm length *Elastica* using SMF 28 fiber and a 1315 nm ELED source. Also shown is the transmission loss for a 10.0 mm *Elastica* using SM 800 fiber and the same light source. Note the large whispering gallery oscillations and apparent breakdown of the theoretical model for the low *V* number SM 800 *Elastica*. The transmission vs. displacement slope at a loss of 50% is $dT/dx = -1.93\text{x}10^{-3}/\mu\text{m}$ for SMF 28 and $dT/dx = -7.9\text{x}10^{-3}/\mu\text{m}$ for SM 800, a factor of 4.1 improvement. However, the strain on the fiber is far less for the SM 800 than for the SMF 28 for a given transmission, due to the decreased SM 800 threshold displacement and steeper slope.

Further improved slope sensitivity is expected for even lower *V* number fiber. The computer model uses the standard bend loss formula modified for the photoelastic effect, but neglects curvature induced field deformation, which becomes more important at low *V* numbers and smaller radii of curvature. Contrary to naïve intuition, the curvature induced field deformation gives significantly lower loss of the fundamental mode [10].

3. Small displacement experimental methods and results

In the experimental arrangement, one end of the SM 800 *Elastica* was mounted near the fixed end of a 140.8 mm long tuning fork tine (288Hz D fork), the other end on a rectangular aluminum rod extending from a motorized micropositioning stage. This allowed for controlled measurement of the transmission vs. displacement curve. Since the micropositioner stage resolution was limited to 200 nm, an aluminum tuning fork was used as a cantilever in conjunction with a magnetic driver in order to obtain controlled and non-hysteretic, subnanometer displacements of the *Elastica*. This was done by attaching a small Nd-B magnet 97.5 mm from the fixed end of the cantilever and using a small solenoid mounted on multiaxis manual micropositioning stages to make a non-contact magnetic actuator.

After obtaining the transmission vs. displacement curve for the 10 mm SM 800 *Elastica*, it was displaced with the motorized micropositioner to a transmission of 46.9%. The magnetic drive was then applied at as low a frequency as possible, 25.391 Hz, so as to yield a minimum detectable signal consistent with the 1/f rise in the noise below about 60 Hz. The first drive amplitude was 10 mV, which produced a signal 24.9 dBV above the noise floor, as shown in Fig. 3 (left). The drive amplitude was lowered by a factor of 10 to 1 mV, and the signal was still observable 6.6 dBV above the noise, corresponding to a measured displacement amplitude of 0.28 nm, Fig. 3 (right).

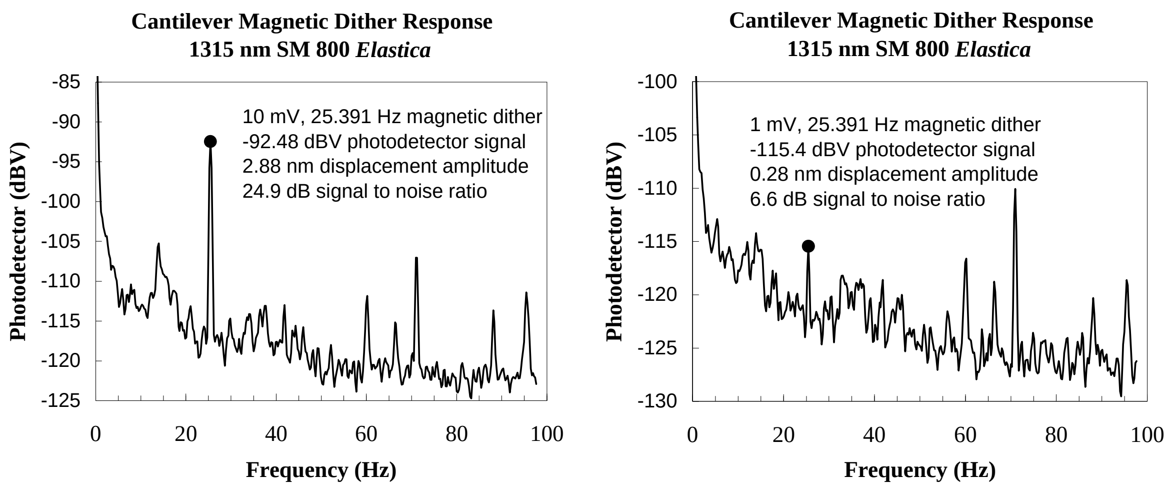


Fig. 3. Magnetic dither signals applied at 97.5mm from fixed end of 140.8 mm long cantilever, showing linear drive scaling and detection of subnanometer displacement (right). *Elastica* mounted 10mm from fixed end of cantilever.

The shot noise limited voltage noise for the detected power of 2.1 μWatts is -139.7 dBV in the 0.244 Hz measurement bandwidth, corresponding to about 17.7 dBV reduction in the present noise floor at 25 Hz. This indicates a shot noise limited sensitivity of 0.036 nm with a 6 dB noise margin. A power of 10 μWatts yields a shot noise limited minimum detectable displacement of 0.016 nm/$\sqrt{Hz}$ with 6 dB noise margin.

4. Conclusion

The detection of low frequency (~25 Hz), 0.28 nm displacements with SNR = 2.1 has been demonstrated with a 10mm *Elastica* sensor and low *V* number single mode fiber. Present sensitivity limited by low frequency source and receiver noise can likely be improved a factor of 10 by employing source modulation and synchronous detection. Further improvements include use of lower *V* number fiber and investigation of the effects of mode field curvature.

5. References

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