Cavity ringdown strain gauge

Peter B. Tarsa, Diane M. Brzozowski, Paul Rabinowitz, and Kevin K. Lehmann

Department of Chemistry, Princeton University, Princeton, New Jersey 08544

Received January 15, 2004

Biconical tapered single-mode fiber, which is common in many telecommunications components, offers an alternative sensor to typical optical fiber strain gauges that are susceptible to temperature and pressure effects and require expensive and sophisticated signal acquisition systems. Cavity ringdown spectroscopy, a technique commonly applied to high-sensitivity chemical analysis, offers detection sensitivity advantages that can be used to improve strain measurement with biconical tapers. Combining these two technologies in a spatially extended resonator, we demonstrate a minimum detectable change in ringdown time of 0.08%, corresponding to a minimum detectable displacement of 4.8 nm, and a sensitivity to strain as small as 79 n$\epsilon/\sqrt{\text{Hz}}$ over a 5-mm taper length.

OCIS codes: 060.2300, 060.2310, 060.2370, 120.4640, 130.6010, 230.5750.

Optical fibers have been widely developed for mechanical strain sensing because of their advantages over traditional mechanical and electrical devices, including high sensitivity, compact size, and immunity from electrical interference.[1] Such fiber-optic sensors generally employ either Fabry–Perot[2] or fiber Bragg grating[3] gauges that cause a strain-induced phase or wavelength shift, respectively, in the propagating field. A biconically tapered single-mode fiber sensor, an alternative to these devices, responds to external strain with an intensity change in the transmitted light, requiring less expensive signal detection and acquisition components with little sacrifice in sensitivity.[4] Biconical taper strain sensing can be further improved by implementation in a cavity ringdown spectroscopy (CRDS) arrangement, resulting in a more sensitive, yet versatile, strain gauge.

CRDS, a technique commonly applied to real-time chemical analysis, measures changes in the decay rate of an optical resonator.[5] Proportional to the losses in the resonator, the ringdown rate is both independent of excitation intensity, resulting in lower susceptibility to laser noise, and immune from external loss contributions, further improving sensitivity. Although typically implemented in a mirror-based cavity, cavity ringdown (CRD) is also an effective method for determining the loss in an optical fiber resonator. Fiber-optic CRD, which has been applied to molecular absorption spectroscopy,[6] refractive-index sensing,[7] and large-scale bending radius measurement,[8] is compatible with biconical tapers distributed along the length of a single-mode fiber resonator.

Single-mode biconical tapers, which have been implemented for evanescent absorption spectroscopy in a fiber CRDS resonator,[6] are low insertion loss modifications in an optical fiber that have found wide application in telecommunications component design.[9] Most commonly created by either chemical etching or axial pulling near the fiber's thermal softening point, biconical tapers induce excitation of low-order cladding modes and then reconvert them to propagating core modes. Although biconical tapers can be fabricated with little insertion loss, the deformities that lead to higher-order mode excitation and loss can be exploited for a variety of sensing schemes. For example, single-mode biconical tapers are extremely sensitive to bending attenuation, in which higher-order cladding modes are excited that have low coupling efficiencies to the guided core modes that emerge from the end of the taper.

Because of the widespread use of single-mode biconical tapers in fiber-optic devices, their response to bending and its application to strain sensing have been both mathematically modeled and experimentally tested.[4,9–11] A careful taper geometry design, with control of the overall length and the minimum waist, allows a balance between linear sensing range and maximum sensitivity. The taper's sensitivity to strain, which is limited by both the slope of the response curve and the noise level of the detection system, is further improved by the signal stability in a CRD system.

We demonstrate this improvement with a 2.2-km fiber-optic CRD resonator, shown in Fig. 1, that was originally developed for evanescent-field absorption sensing. Although many of the design details remain as described in Ref. 6, a few modifications were made to facilitate quantitative strain measurement. Excited by an amplitude-switched diode laser (NEL America Model NLK1556STG, 1520 nm) that is coupled through a 60-dB dual-stage optical isolator

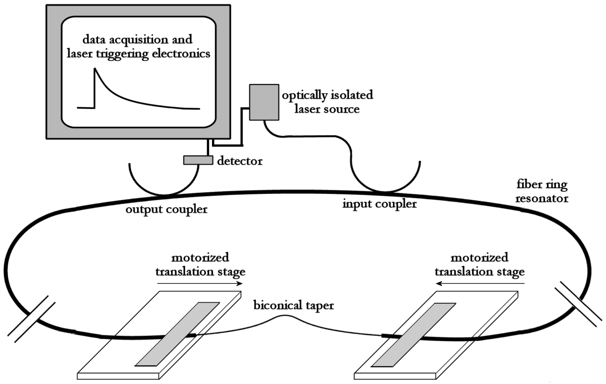

Fig. 1. Schematic diagram of the extended optical fiber CRD strain-sensing apparatus (not drawn to scale).

0146-9592/04/121339-03$15.00/0

(Lightel Technologies), the resonator is formed by standard single-mode fiber (SMF-28e, Corning) fusion spliced into a ring with two 1%/99% split-ratio tap couplers (SMC11501229U, Fiber Instrument Sales). Also incorporated into the resonator, custom-designed single-mode biconical tapers (Lightel Technologies), each of different proportions, are individually spliced between the couplers and fixed to separate, opposing translation stages that are moved by motorized stepper actuators (CMA-25PP, Newport Corporation). The actuators, controlled by a programmable motion controller (ESP300, Newport Corporation), are driven together to bend the taper and to simulate a mechanical strain.

The output of the resonator, which is detected with an amplified InGaAs detector, is digitized with a 12-bit analog-to-digital conversion card and fitted to a single exponential decay by use of a custom fitting routine. Although the fiber resonator signal is somewhat different from a traditional mirror-based cavity output, we have shown that it is sufficiently described by a single exponential that can be linearized, allowing a less computationally intensive fitting routine.[6] Statistical analysis of such multiple ringdown fits is used to determine the resonator stability and to estimate the minimum detectable change in ringdown time, as is common in traditional CRDS.[5]

The response of the CRD device was evaluated by splicing into the resonator a biconical taper with a 10-mm length, an insertion loss of 0.01 dB, and a waist diameter of 30 μm, estimated with an optical microscope. The nonlinear response of ringdown time to displacement, shown in Fig. 2, indicates that the waist of this taper, which was only approximately known, is below the cutoff diameter at which the propagating field cannot be confined to the fiber core. This nonlinearity arises from the excitation of higher-order modes that can be supported by the cladding but have differing coupling percentages to the lowest-order core mode that survives beyond the taper. Such response features remain a significant limitation of the linear range of high-sensitivity single-mode biconcial taper strain gauges.

Although limited, the linear region of this taper can be used to estimate the sensitivity of the CRD device to strain, typically measured in units of microstrain, or $\mu\epsilon$. In this range the standard error in the ringdown time, or the standard deviation divided by the square root of the number of samples, was measured to be 0.0528 μs over 25 ringdown decays. This corresponds to a minimum detectable change in the ringdown time, defined as twice the standard error, of 0.080%, comparable with that measured in other fiber ringdown systems.[6] Over the linear fit shown in Fig. 2, this noise level indicates a minimum detectable displacement of 74 nm, or a sensitivity to strain as small as 7.4 $\mu\epsilon$ over the 10-mm taper length. To take advantage of this sensitivity, we can further extend the working range for strain sensing with this specific taper design beyond the linear region by employing an experimental calibration curve, as mode conversion over an extended range is constant and predictable, although mathematically complicated.[9–11]

Biconical tapers of different dimensions were examined to find the limitations of CRD strain sensing, as well as the optimal gauge proportions for strain sensitivity. Because the slope of the taper's response is derived from its geometric proportions, we tested a set of biconical tapers, each with a 25-μm waist diameter and lengths of approximately 5 and 15 mm. The response of these tapers, shown in Fig. 3, confirmed our expectations that shorter lengths, or more severe taper angles, improve sensitivity, showing minimum detectable strains of 2.8 and 48 $\mu\epsilon$ over 5.40 and 14.8 mm, respectively. Assuming that 1000 ringdown decays can be acquired and fitted in 1 s, this corresponds to a maximum sensitivity of 79 $\text{n}\epsilon/\sqrt{\text{Hz}}$ with the 5.40-mm taper.

Further improvement in sensitivity is possible either by increasing the taper angle, and thus the slope of the response, or by improving the stability of the ringdown time. The maximum taper angle is ultimately bound both by the physical strength of the taper, which decreases with the taper waist, and by the transmitted signal intensity, which is limited by increased

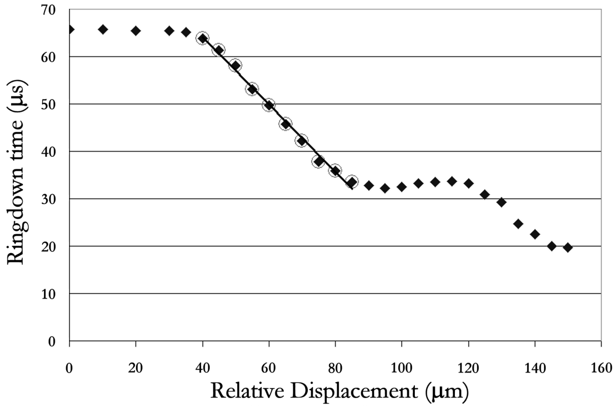

Fig. 2. CRD strain response. The linear region of the CRD signal, defined by the circled points, has $R^2 = 0.9935$. With this taper, the linear range covers 45 μm, or 4500 $\mu\epsilon$, with a minimum detectable displacement of 74 nm, or 7.4 $\mu\epsilon$, over the 10-mm taper.

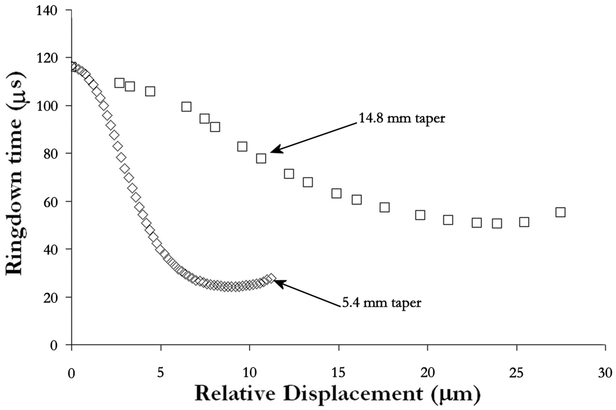

Fig. 3. Comparison of biconical tapers with a 25-μm waist, labeled by length. Shorter tapers, which have more severe taper angles, show increased sensitivity to strain but have a limited linear range.

insertion loss. Operating with sufficient signal intensity, a CRD arrangement is able to measure small changes in ringdown time that are not discernible as intensity fluctuations.[5] CRD measurement, which is enhanced both by minimizing system noise and by decreasing the ringdown rate, could be optimized in this system by reducing the sources of loss, such as the fusion splice loss and the bulk loss in the fiber, and then matching to it the coupling ratio of the input–output couplers. However, the high intrinsic loss in a fiber resonator limits system stability and thus the minimum detectable change in ringdown time from the levels that have been demonstrated in traditional mirror-based CRDS devices. Comparison of the ensemble uncertainty in several decays to the measured noise in the fit of a single ringdown indicates that long-term system noise is not a significant factor in this device, suggesting that the response of the taper is the limiting element.

We have demonstrated a practical device for strain sensing in an extended optical fiber resonator by combining the sensitivity of CRD, typically applied to chemical sensing, with the versatility of biconically tapered single-mode fiber. By prebending a taper to operate in its linear response region, this device is capable of noise-equivalent measurement of the order of 1 $\mu\epsilon$. This sensitivity, of the same order of magnitude as that reported for several Fabry–Perot[2] and FBG[1] strain gauges, is achieved without the expensive acquisition and processing components used with these other types of optical fiber strain gauge. Furthermore, the insensitivity of biconical tapers to temperature and pressure changes compliments the benefits of other optical fiber strain gauges without sacrificing their characteristic sensitivity. The versatility of optical fiber strain sensing in a single-mode bioncial taper is complimented by the sensitivity of CRD, resulting in a simple, inexpensive device for sensitive strain sensing.

This work was supported by a National Science Foundation Small Grant for Exploratory Research (CHE-0228977). We also thank Tiger Optics, LLC, for the donation of key equipment. K. K. Lehmann's e-mail address is lehmann@princeton.edu.

References

1. B. Lee, Opt. Fiber Technol. **9,** 57 (2003).
2. T. Valis, D. Hogg, and R. M. Measures, IEEE Photon. Technol. Lett. **2,** 227 (1990).
3. S. M. Melle, K. Liu, and R. M. Measures, Appl. Opt. **32,** 3601 (1993).
4. F. J. Arregui, I. R. Matias, and M. Lopez-Amo, Sensors Actuators **79,** 90 (2000).
5. J. B. Dudek, P. B. Tarsa, A. Velasquez, M. Wladyslawski, P. Rabinowitz, and K. K. Lehmann, Anal. Chem. **75,** 4599 (2003).
6. P. B. Tarsa, P. Rabinowitz, and K. K. Lehmann, Chem. Phys. Lett. **383,** 297 (2004).
7. M. Gupta, H. Jiao, and A. O'Keefe, Opt. Lett. **27,** 1878 (2002).
8. T. von Lerber and M. W. Sigrist, Appl. Opt. **41,** 3567 (2002).
9. J. D. Love, W. M. Henry, W. J. Stewart, R. J. Black, S. Lacroix, and F. Gonthier, IEE Proc. J **138,** 343 (1991).
10. R. J. Black, S. Lacroix, F. Gonthier, and J. D. Love, IEE Proc. J **138,** 355 (1991).
11. P. M. Shankar, L. C. Bobb, and H. D. Krumboltz, J. Lightwave Technol. **9,** 832 (1991).