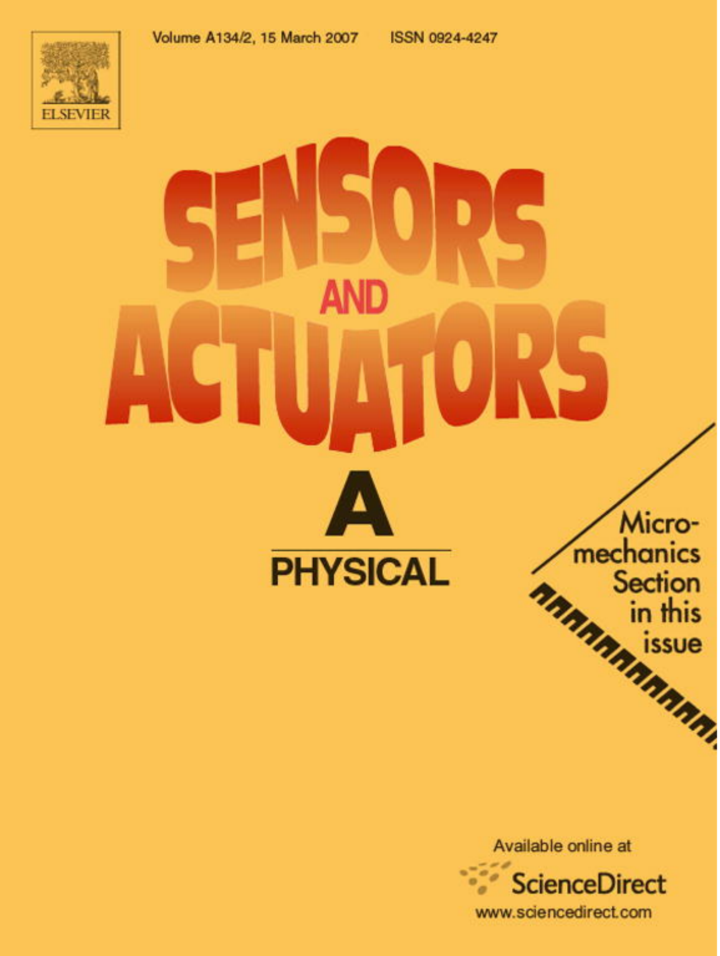
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Frequency-domain displacement sensing with a fiber ring-resonator containing a variable gap

Frank Vollmer*, Peer Fischer

The Rowland Institute at Harvard, Harvard University, Cambridge, MA 02142, United States

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Abstract

Ring-resonators are in general not amenable to strain-free (non-contact) displacement measurements. We show that this limitation may be overcome if the ring-resonator, here a fiber-loop, is designed to contain a gap, such that the light traverses a free-space part between two aligned waveguide ends. Displacements are determined with nanometer sensitivity by measuring the associated changes in the resonance frequencies. Miniaturization should increase the sensitivity of the ring-resonator interferometer. Ring geometries that contain an optical circulator can be used to profile reflective samples.

Keywords: Ring-resonator; Optical fiber; Displacement sensing; Optical resonance; Reflectance metrology; Optical circulator

1. Introduction

Optical interferometers are based on the interference of two or more light beams derived from the same source. The sensitivity of classical two-beam interferometers, of which the Michelson and Mach-Zehnder interferometers are well known examples, can be surpassed in geometries that permit multiple-beam interference, such as in a Fabry–Perot etalon or a ring-resonator [1,2]. Closed-loop multiple-beam interferometers in the form of ring-, disk- or toroid-resonators have recently attracted considerable attention due to the simplicity of their fiber- or chip-based design and their potential for micro-fabrication with high finesse and high quality factors [3–6]. These resonators hold great promise for use as chemical and biochemical sensors [7–10].

Ring-resonators (RRs) have also been proposed as displacement sensors based on strain-induced, reversible changes of the ring circumference, e.g. for atomic-force-microscope cantilevers [11]. However, this approach may be limited since it relies on deformation of the resonator and since strain-induced refractive index changes complicate the relationship between cantilever displacement and resonance frequency. Although fiber loop ring-resonators may respond linearly to a small strain and this finds application in piezoelectric fiber stretchers for the purpose of optical phase control [12], closed-loop geometries are incompatible with strain-free (non-contact) displacement measurements.

Here we show that this limitation may be overcome, if the ring-resonator is designed to contain a gap. Changes in the size of the gap between the aligned waveguides are determined from a shift of the resonance wavelength of a fiber-based RR. We demonstrate that the use of a narrow-linewidth continuous-wave laser permits measurements of sub-wavelength displacements simply by tuning the laser diode current and therefore its operating frequency. This circumvents the need for absolute intensity measurements. The sensitivity of our ring-resonator interferometer to displacements is expected to increase as its overall dimension is reduced, which may be of interest to microfiber-loop resonators [4].

2. Background

Optical resonances in a ring-resonator require that the optical path-length is a multiple of the wavelength λ of the light. Resonances are observed as minima in a transmission spectrum [13] on a photo-detector whenever an integral multiple m of the wavelength in the ring equals the circumference C (fiber and

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* Corresponding author. Tel.: +1 6174974681; fax: +1 6174974627.
E-mail address: vollmer@rowland.harvard.edu (F. Vollmer).

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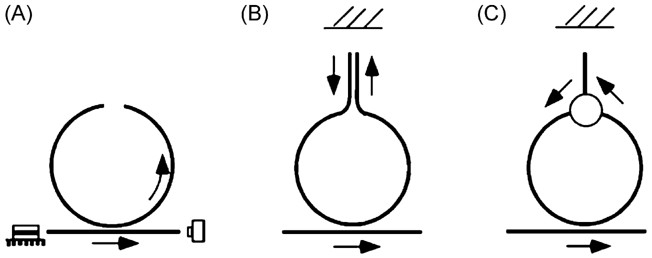

Fig. 1. (A) Ring-resonator with a variable gap, evanescently coupled to a bus waveguide. A tunable, narrow-linewidth laser is connected to the bus waveguide and a photodetector records the transmission spectrum. Profiling of a reflecting sample surface is possible for geometries where two fiber ends are aligned (B), or where a circulator is part of the ring (C).

free-space part) of the fiber-loop:

$$n_{\mathrm{eff}}C = m\lambda, \tag{1}$$

where n_{eff} is an effective index used to describe the entire fiber-loop resonator with unperturbed gap. n_{eff} corresponds to the round-trip phase $2\pi n_{\mathrm{eff}}C/\lambda$ acquired by a resonant mode at λ. If the waveguide part of the ring-resonator remains unperturbed, then a shift in the resonance wavelength occurs if either the dimension of the gap or the refractive index (medium) in the gap changes. We have recently shown that the latter can be used to measure refractive indices and circular birefringences (optical activities) in the frequency domain [8]. A change ΔL in the gap dimension results in a shift $\Delta\lambda$ of the resonance wavelength

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta L}{C}. \tag{2}$$

3. Experiments and results

In the present study the gap contains air and only its dimension is changed. In its simplest form the gap is defined by two aligned, cleaved waveguide ends (see Fig. 1A). However, different geometries allow for non-contact profiling of a partially reflecting surface (Fig. 1B), and use of a circulator allows displacement measurements with only one fiber or waveguide end (Fig. 1C).

Our experiments are based on a fiber-loop ring-resonator (see Fig. 1A) built with a single mode 50/50 fiber coupler, where one output port of the coupler is connected back to an input-port [3]. The circumference of the ring is ~0.63 m. A 20 mW tunable, narrow-linewidth, distributed feedback (DFB) laser diode operating at ~1311 nm nominal wavelength is connected to the bus waveguide through an optical isolator. The transmitted intensity is recorded by an InGaAs photodetector. We tune the laser frequency by modulating the diode current with a saw-tooth shaped function. The laser diode tuning coefficient has been determined with a wavemeter and is ~0.0067 nm/mA. The scan frequency is typically 100–300 Hz, and 1000 points per transmission spectrum are recorded with a computer. The dynamic range in the present setup is limited due to real-time data analysis in Labview, but in principle the laser diode current could be modulated at MHz to GHz frequencies. Resonances appear as Lorentzian-shaped dips (Fig. 2A). The computer determines the resonance wavelength λ from the recorded transmission spectrum with a parabolic minimum fit using ~20 points, and tracks its change Δλ.

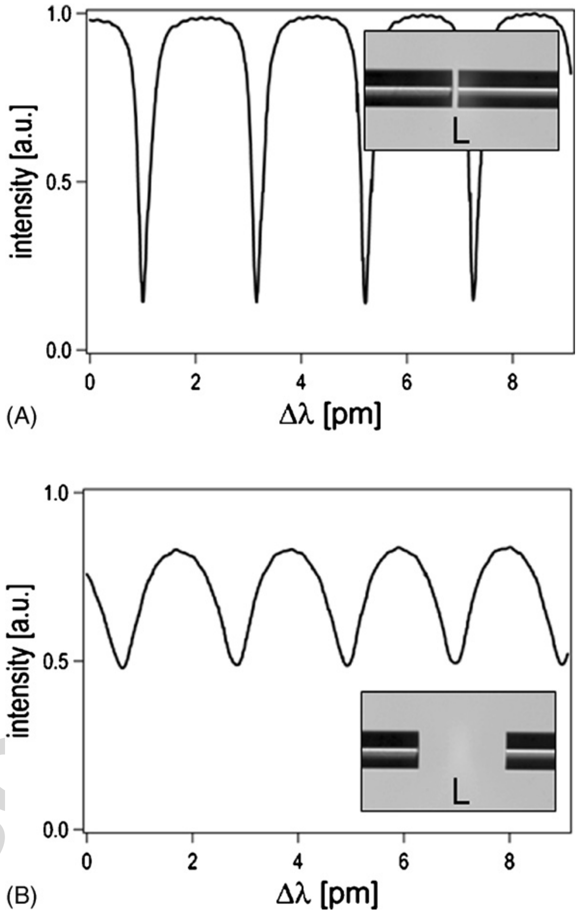

Fig. 2. (A) Transmission spectra of a ~0.63 m fiber-loop ring-resonator with gap of length $L \sim 10\,\mu\mathrm{m}$, recorded with a tunable DFB laser of ~1311 nm nominal wavelength. Resonances appear as Lorentzian dips with a finesse ~7.8. The inset shows the cleaved ends of the single mode fiber, 125 μm in diameter. The fiber ends are aligned with two opposed, three-axis stages. (B) Transmission spectra for the same fiber loop with a larger gap, $L \sim 300\,\mu\mathrm{m}$ and finesse ~2.8. The inset shows a picture of the aligned fiber ends.

A variable gap of nominal length L (insets in Fig. 2A and B) is introduced by cleaving the closed fiber loop at one point and aligning the fiber ends using two, three-axis mechanical stages equipped with piezoelectric actuators. Fig. 2A and B show the transmission spectra for two fixed gap lengths of L ~10 and ~300 μm with finesse of ~7.8 and ~2.8, respectively. The gap length can be changed by a small distance ΔL through modulation of the piezo actuators with a control voltage (64 $\mathrm{mV_{P\text{-}P}}/\mu\mathrm{m}$) set by an arbitrary waveform function generator.

In Fig. 3 we demonstrate that the shift of the resonance wavelength Δλ directly follows the gap displacement ΔL. Fig. 3A depicts the gap and Fig. 3B the modulated gap length ΔL (dotted line) and the corresponding shift of the resonance wavelength Δλ (solid line). The 3 Hz carrier is amplitude modulated at 0.15 Hz, such that ΔL changes by as much as ±0.225 μm.

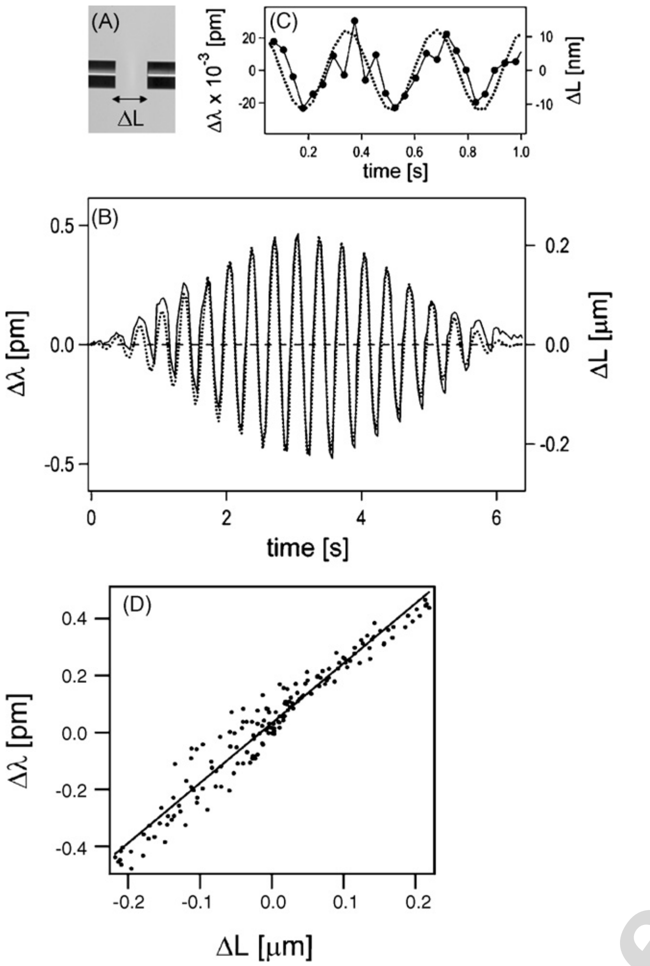

Fig. 3. (A) Illustration of a gap of variable displacement ΔL. (B) The gap displacement ΔL is modulated ±0.225 μm with piezoelectric actuators and plotted vs. time (dotted line, displacement scale for ΔL on right axis). The resonance wavelength shift $\Delta\lambda$ of the ring-resonator is a direct measure of the gap displacement and plotted in the same graph (solid line, wavelength scale for $\Delta\lambda$ on left axis). (C) A gap displacement of $\Delta L \sim 10$ nm is measured from the corresponding shift $\Delta\lambda$ (~0.024 pm) of a resonance wavelength in a ~0.63 m fiber-loop ring-resonator. (D) Shift of the resonance wavelength as a function of displacement (data from (B)), where the straight line is a linear fit to the data.

An estimate of the sensitivity of the current setup with a ~0.63 m ring can be obtained from the data in Fig. 3C, where a ~10 μm nominal gap length is modulated sinusoidally with an amplitude of $\Delta L = 10$ nm at 3 Hz. It is seen that subwavelength (~10 nm) displacement measurements are already possible with the relatively large, low-finesse fiber loop resonator. The magnitude of the associated wavelength shift $\Delta\lambda$ is ~0.024 pm, or about 1/10th of the linewidth (~0.28 pm, corresponding spectrum is shown in Fig. 3A). The shift of the resonance wavelength $\Delta\lambda$ is inversely proportional to the overall length (circumference) C of the ring-resonator, and is given by Eq. (2). It follows that smaller ring-resonators of similar geometry and linewidth allow for even smaller displacement measurements. From Eq. (2) it is seen that sub-nanometer sensitivity can be expected from a fiber-loop resonator with a circumference ~1 cm, which could be microfabricated or built from a tapered fiber [4].

4. Discussion

The current measurements are susceptible to overall drift. Common-mode noise may be eliminated by tracking the relative shift between resonances [8]. For example in a geometry such as the one shown in Fig. 1C a mode can give rise to two distinct resonances if in addition to the reflection at the surface, it is partially back reflected at the (possibly coated) fiber tip. In this configuration the ring-resonator may be applied in measurements where conventional (i.e. non-circular and mirror-based) Fabry–Perot resonators have been successfully used, e.g., for thin-film characterization by displacement spectroscopy [14] or for fiber-optic vibration and displacement sensing [15,16] or for pressure sensing [17]. Similarly, it may be possible to use orthogonally polarized modes for relative shift measurements, provided the coupling of the modes can be suppressed [8].

An increase in finesse and thus sensitivity of the ring-resonator can be expected, if optical losses are compensated for, e.g., by optical amplification as demonstrated for a closed fiber-loop resonator that contains a section of pumped Erbium-doped fiber [18]. Furthermore, the fiber ends could hold provisions such as gradient refractive index lenses for efficient waveguide-coupling.

5. Conclusion

In summary, we demonstrate that lateral displacements can be measured in the frequency domain with a narrow-linewidth laser by tracking the resonance wavelength of a suitable resonator. We show that introduction of a gap enables a RR to be used for non-contact waveguide-displacement measurements. A single mode, variable gap fiber-loop ring-resonator with a circumference of ~0.63 m connected to a tunable DFB is shown to be sensitive to displacements of ~10 nm. Dramatically smaller waveguide displacements should be measurable in rigid, micro-fabricated resonators containing one or more gaps or in RRs that contain an optical circulator.

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Biographies

Frank Vollmer is currently a Junior Fellow at The Rowland Institute at Harvard. He received his M.S. in Biochemistry in 1998, and his Ph.D. in ‘Physics in Biology’ from The Rockefeller University, New York, in 2004. For his master thesis he worked in Dr. Robert Roeder’s laboratory of Biochemistry on the characterization of a eukaryotic transcription factor. His Ph.D. thesis was supervised by Dr. Albert Libchaber; the work in experimental physics concerned perturbations of high-Q optical microcavities with nanoparticles and biomolecules for detection and analysis. He received a scholarship from the Boehringer Ingelheim Fonds, Germany.

Peer Fischer received his BSc. degree in Physics from Imperial College London in 1995. He obtained his Ph.D. in Chemistry from the University of Cambridge in 1999, working under the supervision of A.D. Buckingham. His thesis work concerned the nonlinear optical properties of chiral media. Prior to joining the Rowland Institute at Harvard, he was a visiting scientist at the European Laboratory for Nonlinear Spectroscopy in Florence, and a NATO Postdoctoral Fellow at Cornell University. His research interests are in the optical, magnetic, and electric properties of matter with a particular emphasis on chiral molecules.