Asian Journal of Physics
Vol. 31, Nos 3-6 (2022) A27-A32
Available on: www.asianjournalofphysics.com
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Design, experimental demonstration and modeling fiber ring resonator device with fiber cantilever-deflection probe for sensing surrounding electric field

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Dedicated to Professor Bishnu P Pal for his enormous contributions to the advancement of research and education in science and technology through his unique vision and outstanding dedication

In this report, we describe design, experimental realization and demonstration of a direct coupled fiber ring resonator having a fiber cantilever-deflection transducer in the ring loop for sensing the electric field in the vicinity. The transducer probe is the free end of the fiber forming the loop whose tip is coated with cobalt-modified bismuth ferrite nanoparticles forming a deflecting fiber cantilever. We performed a series of experiments to investigate the observed resultant variation of resonance patterns in the environment of varying electric field. We successfully demonstrate a sensitivity of 0.05 kV/cm in the dynamic range of 0 – 0.75 kV/cm. We provide a theoretical platform to model the working principle of the cantilever-based fiber resonator. The transmission characteristics of our model precisely mimic the experimental transmission signature, thereby establishing the efficacy of the model that defines the operating principle of the device.

Keywords: Fiber-optic sensor, Cantilever beam deflection, Fiber ring resonator, Electric field sensor.

1 Introduction

In recent years, the optical ring resonator has emerged as a promising technology in the area of photonic devices and fiber optic circuits. A fiber ring resonator is an all-fiber device which is highly sensitive and offers excellent performance as a sensor for detection and measurement of various external measurands and this in turn, has pushed a huge research efforts to develop devices and explore new potential applications [1,2]. Fiber ring resonators are very unique as regards the multi-pass/all-pass nature of signal modulation by the external perturbation imparted to the loop. When the light at the resonant wavelength propagates through the fiber loop, due to multiple round-trips, the light builds up in intensity because of constructive interfrence resulting in an enhanced response that is intrinsic to the configuration. Every time the light circulates in the loop, a transducer gain by a factor of half is yielded resulting in a cumulative gain multiplication. Furthermore, being a fiber based resonator it enjoys all the advantages of fiber devices, namely, small size, light weight, flexibility, high sensitivity, robust design, and most importantly, guided mode sensing and the capability of remote and multiplexed interrogation. In addition, the single-mode all-fiber ring resonators are used in making passive fiber gyroscopes [3,4], frequency-selective devices [5], an all-fiber resonator interferometer [6,7], lasers [8-10], optical filtering [11,12], optical time delay [13]. These loop resonators are demonstrated for the measurement of internal stress, pressure [14,15], temperature [16, 17], humidity [18] and other associated parameters. Notably, these fiber resonators proved excellence in biochemical and medical sensing [19-22].

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The pioneer research groups across the worldwide have explored optical ring resonators with fiber and different waveguide structures or designs for thorough study. In 2017, Chandran *et al* fabricated an all fiber ring resonator with silicon-on-insulator waveguide that can be significantly used for refractive index sensing [23]. Also, based on evanescent field interaction Linslal *et al* demonstrated an optical fiber loop resonator used for chemical sensing [24]. Using a direct-coupled fiber ring resonator, Vollmer and Fischer designed a frequency-domain displacement sensor which contains a variable gap [25]. In addition, mode conversion of the optical signal has been described by Bharti *et al* using single waveguide coupled silicon micro-ring resonator [26].

Following these developments, we designed and fabricated a direct-coupled ring resonator configuration with a fiber cantilever in the loop for sensing electric field. The operating principle is based on the shift of the interference dip due to the interaction of propagating light field with the surrounding environment that is enveloped by the cantilever deflection based coupling and modulation of signal in the resonator ring. Furthermore, the ring resonator with a fiber cantilever based coupling behaves as a Fabry-Perot cavity only, in which cavity modes can be controlled by varying experimental parameters. A theoretical analysis of the transmittance of our modified configuration is also provided for a clear understanding of our experimental findings. For fabricating such sensors, the key issue is to choose an appropriate probe material that exhibits a higher response after interaction with the applied electric field. We choose cobalt doped bismuth ferrite nanoparticles as electric probe material as reported in our previous findings [27].

2 Experimental details and Results

In this section, we describe the experimental method and the operating principle for sensing electric field using direct-coupled fiber ring resonator configuration.

2.1 Cantilever-beam deflection arrangement experimental technique

As shown in the schematic of the experimental setup (Fig 1), light from the He-Ne laser source (632nm, 5mW) is focused using a 40X microscopic objective into the input port of a 3dB coupler (@ 632 nm). The tip of the coupled port is coated with cobalt modified bismuth ferrite nanoparticles which act as the electric-probe material. The tip remains freely suspended forming a cantilever and is placed head-on with another input port of the 3dB coupler between two electric field plates using 3d translational stages thereby forming a direct-coupled fiber loop ring configuration. Thus, the optical fiber circuit so formed acts as the Fabry-Perot loop with two series coupled cavities - a fiber loop with a variable air-gap cavity. The output is taken from direct port (port 3) as shown in the Fig 1. In our experimental setup, the coated length of the fiber is 1± 0.1 cm with coated thickness of 0.32 µm, as optimized from our previously reported single cantilever arrangement [27].

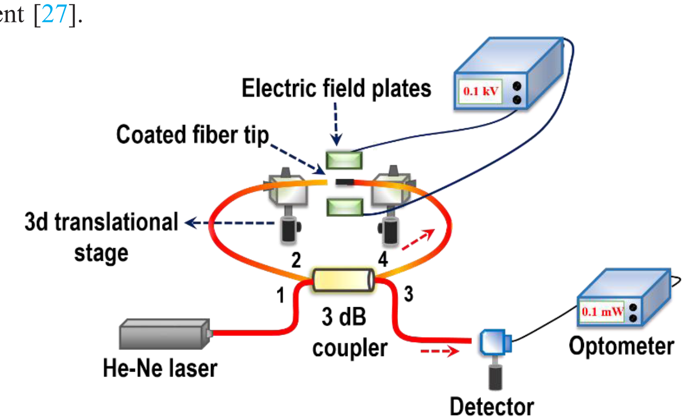

Fig 1. Schematic of experimental set-up used for cantilever arrangement.

Initially, off-sets adjustment is made between the optical fibers in the loop using the 3d translational stages independently to achieve the resonance condition. When an electric field is applied, the fiber bends in the transverse direction due to the induced polarization of the probe nanocomposite, creating a misalignment in coupling between adjacent fiber tips that modifies the effective optical path in the loop.

We performed a series of experiments to maximize the performance of the cantilever deflection as a function of electric field and quoted here are the typical results of power transmittance for cantilever lengths of 3.0 cm and 2.8 cm, respectively as converged value. The separation between the electric plates remained at a distance of 1 cm. The circumference of the fiber ring (*L*) is ~ 0.5m. The response curve recorded for this setup using photodetector-powermeter (Newport model) setup for varying electric field is shown in Fig 2. The slightly longer cantilever, clearly exhibits a relatively better modulation. Close to the optimized cantilever size, the longer one shows more flexibility and response in deflection as seen in the recorded plot.

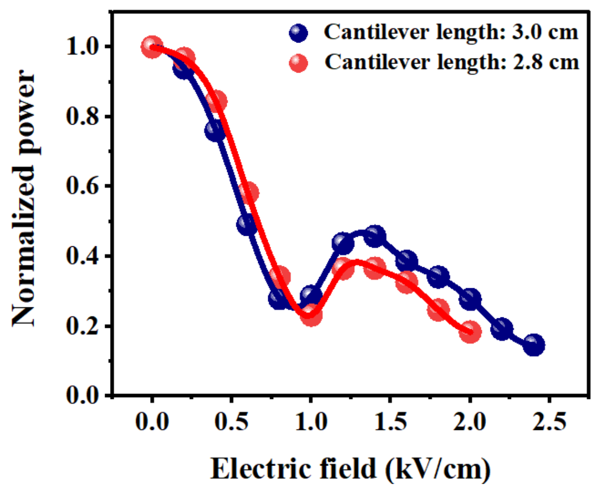

Fig 2. Normalized output intensity variation with application of electric field.

It is evident from the above experimentally obtained transmission characteristics of the fiber cantilever based ring resonator that sensitivity is the maximum within the first cycle of transmission signature of the resonator. From Fig 2, it can be noticed that in the dynamic range of 0 - 0.75 kV/cm of an electric field, our modified scheme's sensitivity is high with a minimum electric field detection limit of 0.05 kV/cm.

2.2 Theoretical model

We next model the behavior of the fiber circuit in terms of cantilever deflection forming a modulation envelope to the circulating signal in the resonator loop. In general, the transmitted output intensity from the direct port (port 3) of the fiber ring resonator configuration is given by [28, 29]:

$$\left|\frac{E_3}{E_1}\right|^2 = (1-\gamma_0)\left[1 - \frac{\kappa(1-\kappa-A)/(1-\kappa)}{1 + A - 2A^{1/2}\cos(\beta L)}\right] \tag{1}$$

where E_3 and E_1 are the electric field amplitudes at Port 3 and Port 1, respectively, γ_0 is the coupler insertion loss, κ is the coupling coefficient, β is the optical propagation constant and L is optical loop length. Hence, βL is the total phase shift experienced by the light wave after one complete turn in the fiber loop. The quantity A is defined as

$$A = (1-\kappa)\,(1-a_0)(1-\gamma_0)\,e^{-2\alpha L} \tag{2}$$

where, a_0 is the splice loss (intensity) and α denotes fiber attenuation.

Now, in our cantilever modified fiber loop scheme, the transmitted output intensity is expressed as,

$$\left|\frac{E_3}{E_1}\right|^2 = (1-\gamma_0)\left[1-\frac{\kappa(1-\kappa-A)/(1-\kappa)}{1+A-2A^{1/2}\cos(\theta'(E))}\right] \tag{3}$$

Here, $\theta' = (\kappa n_{eff} L + \kappa n_{air}\,\Delta L)$ is the sum of initial phase due to length L of fiber loop and additional phase shift experienced due to deflection of the coated fiber which results in incremental change in L by ΔL.

The Gaussian-profile transmission model of the fundamental mode coupling through cantilever junction of this fiber ring device as a function of transverse misalignment/deflection (Δ) caused by the surrounding electric field can be written as [30]:

$$T = \left(\frac{2\omega_1\,\omega_2}{\omega_1^2+\omega_2^2}\right)^2 e^{-2\Delta^2/(\omega_1^2+\omega_2^2)} \tag{4}$$

where T is the transmitted power coupled into the receiving fiber, ω_1 and ω_2 are the spot size of the respective optical fibers. As is well known, it is evident from Eq (4) that the transmitted power decays exponentially with the deflection Δ causing misalignment. In our modified fiber loop configuration, the modulation of the output power is associated with two different mechanisms: the periodic power variation pattern as a function of loop fiber length (Fig 3(a)) and exponential decay because of power coupling between two optical fibers (Fig 3(b)).

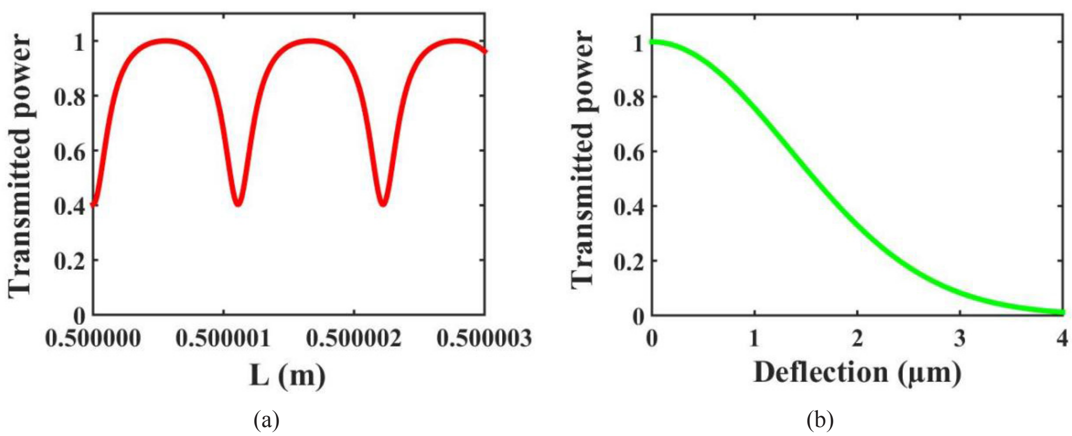

Fig 3. (a) Resonance output intensity as a function of fiber loop length in direct coupled configuration. (b) Transmitted intensity variation with increasing transverse misalignment between the two fibers forming cantilever deflection-coupling probe.

The modulation in the fiber loop length due to bending of the fiber is modeled through an expression $\Delta L = m\Delta$, where m is a constant. From our previous study, it has been established that the deflection of the coated fiber varies nearly linearly with applied electric field (E), i.e. $\Delta = pE$ (p = constant) in the small deflection limit [27]. We modeled the theoretical response of our experimental scheme, shown in Fig 2 by incorporating the effect of varying ΔL yielding phase modulation ($\kappa n_{air}\Delta L$) as given in Eq (3). Using this model of transmission of the resonator ring modulated by cantilever-deflection coupling as envelop, our computed transmission characteristics of the modified resonator loop configuration shown in Fig 4, nicely mimics the experimentally observed signature (Fig 2) for the lower regime of applied electric field. While quantitatively mapping the experimentally observed data, the theoretical value of splice loss (a_0) is taken as 0.25 dB, the coupler insertion loss (γ_0) as 0.01 dB and the fiber attenuation loss as 0.5 dB/km, these values are well within the practical range and are quoted as commercial/manufacture's values. Thus, through this study, our new experimental design of cantilever-deflection based fiber ring resonator configuration for sensing surrounding electric field is demonstrated. We show that sensitivity as good as 0.05kV/cm can be achieved by this new design of single-mode fiber based ring resonator device. Importantly, we devise an accurate theoretical model by embedding the modulation of fiber cantilever-deflection in the transmission of a fiber ring resonator and successfully interpret the experimentally observed results of our in-house designed experimental prototype.

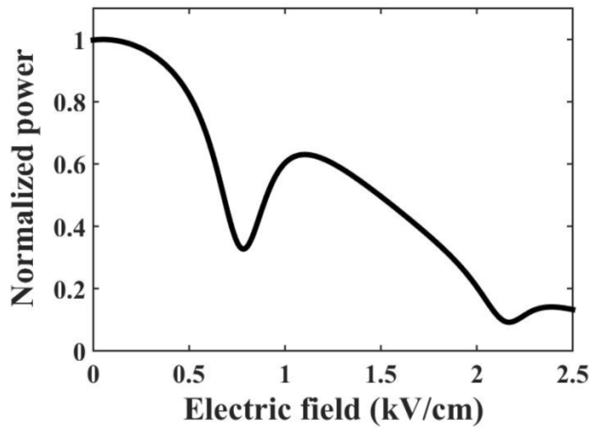

Fig 4. Computed response of the fiber ring resonator with electric field using cantilever configuration.

3 Conclusion

In this study, we report our experimental investigation, analysis and results pertaining to the transmission characteristics of direct-coupled fiber ring resonator containing a fiber cantilever beam-deflection transducer arrangement in loop for measuring electric field in the vicinity. The cantilever design is optimized in order to have a high performance modulation of the signal circulating in the fiber ring resonator. We demonstrate experimentally that a minute change of electric field 0.05kV/cm in the surrounding can be ambiguously detected by our all-fiber device in the range of 0 – 0.75 kV/cm. To understand the effect of cantilever modulation of circulating signal in the resonator loop, we modeled the behaviour theoretically on the basis of the known transmission characteristics of these fiber devices. The analysis exhibits excellent agreement of the theory with the recorded experimental data. The sensitivity of this electric field sensor can be further tuned by suitably controlling the cantilever design and exploring more sensitive probe material.

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[*Received*: 15.06.2022; *accepted*: 30.06.2022]

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