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Demonstration of gain multiplication by series assembly of fiber-optic cantilever beam deflection: Measurement of low magnetic field and magnetization of probe samples

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ABSTRACT

We report our experimental realization of fiber-cantilever beam-deflection magnetometer using a series assembly of deflecting fiber-cantilevers for measuring low magnetic field (~mT) and magnetization of probe nano-particles. Using single-mode fibers coated with optimized cobalt-doped-nickel-ferrite nano-particles, we devise a concatenated twin-fiber-cantilever assembly that identically modulate transmitted fiber-exit beam with varying external magnetic field. We measure surrounding field as low as ~1 mT and demonstrate gain-multiplication through series-fed signal of fiber-cantilever response. Our cantilever-deflection-transmission analysis is devised to interpret the experimental observation and to determine magnetization of probe-samples. A Sagnac-loop assisted cantilever arrangement is also fabricated and tested that yielded the same sensitivity.

1. Introduction

A new technology involving micro-thin cantilevers of different types (a plate, beam or a thin membrane) has attracted much interest in the area of sensing and device applications [1–3]. For example, a Si cantilever with iron sample attached onto it was used by R. Adhikari et al. for studying the magnetization and magnetostrictive behavior of the sample by measuring the deflection of the cantilever in a magnetic field using optical method [4]. In addition, T. Chu Duc et al. demonstrated a nano-Newton resolution force sensing cantilever structure that detects both the lateral and vertical forces using an electronic circuit [5]. Apart from these, the cantilever techniques are most often used in environmental monitoring [6], temperature [7], humidity [8], UV radiation [9], stress [10] sensing and device applications. Because of its low cost and scalability, this technique has found enormous applications in medical, chemical and biochemical measurements also [11–14]. Among all these techniques, fiber-optic cantilever technique is a new member and admits of considerable attention due to inherent flexibility, small size, capability of remote sensing and multiplexed operation. Fiber-optic cantilever sensor is generally either purely fiber based or fiber-chip based integrated cantilever structures. A fiber-to-chip cantilever coupler scheme was described by P. Sun et al. for silicon photonic device applications [15]. Y. Zhao et al. developed a fiber-optic cantilever type tilt measurement scheme using a pair of fiber Bragg Gratings [16]. Apart from these, the fiber-optic cantilever scheme has find widespread applications in the area of temperature, acceleration, weight, force, flow rate measurement and health monitoring also [17–19]. For decades, measurement of magnetic field using all-optical, remotely addressable and flexible fiber based system, is the topic of interest for many researchers. However, most of the reported measurement schemes are associated with the induced longitudinal strain measurement caused by applied magnetic field [20–22]. Temperature cross-

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sensitivity is a big issue for these types of sensors. Besides, many of these sensing configurations require complex hardware or signal analyzing system and that limits their area of application.

With this stand in mind, we attempted devising a fiber-optic cantilever based sensor configuration which will be capable of detecting low order magnetic field with minimum system complexity. The proposed sensing scheme would be suitable for remote sensing, in particular at hazardous environment where electrical probes cannot be deployed. For designing such type of sensors, choice of proper probe magnetic material is the key issue. Spinel type oxide, Cobalt-doped nickel ferrite ($Ni_{0.97}Co_{0.03}Fe_2O_4$) was reported in literature for its exceptionally high magnetic properties [23,24] and was used by M. Sedlar et al. for devising a Mach-Zehnder interferometer type magnetic field sensor [25]. Consequent upon these findings, Cobalt-doped nickel ferrite ($Ni_{0.97}Co_{0.03}Fe_2O_4$) nano-composite was chosen as our probe magnetic material. Characterizations in different forms established its noble performance as probe material of super paramagnetic nature. Detailed preparation methodology and characterization results were reported in our previous work [26]. In that research, we demonstrated the efficacy of single-cantilever fiber-to-fiber transmission arrangement in measuring weak magnetic field (~20 mT) in the surrounding. Effect of chemical etching of cantilever fiber was also incorporated towards improving the sensitivity further. Based on the success of this scheme, we conceived of common-mode gain multiplication of the system by reconfiguring cantilever model to series assembly of fiber-cantilever beam deflection arrangement. In a process continued experiments and series studies we could improve the measurement sensitivity drastically using etched fiber forming cantilever assembly. In this paper, we detail our modified setup yielding more useful experimental results pertaining to this redefined version of the fiber beam-deflection magnetometer with the optimized Cobalt-doped nickel ferrite ($Ni_{0.97}Co_{0.03}Fe_2O_4$) as probe material. The efficacy of our newly adopted method is validated through comparing the results with those obtained from single-cantilever setup. A theoretical model is also provided to support experimentally obtained results. Magnetization value of the probe magnetic sample is obtained from experimental results using the theoretical formulation. We also demonstrate the effect of increasing number of cantilevers and chemical etched fibers in the setup towards measuring even lower order magnetic field. In the following we detail our cantilever beam deflection configuration, typical experimental results in the platform of our devised cantilever-deflection-transmission model.

2. Coating material: probe magnetic sample

Cobalt-doped nickel ferrite ($Ni_{0.97}Co_{0.03}Fe_2O_4$) sample was prepared from nitrate salts of iron, nickel and cobalt by using sol-gel method [27]. Details of the preparation methodology are discussed in our former reported work [26]. Here, we quote the end characterization results to evidence the structural morphology and magnetic behavior of our probe material which we have used to develop weak magnetic field sensing configuration. The crystalline structure and magnetic properties of the prepared probe material were investigated respectively by XRD analysis and SQUID measurement. The estimated lattice constant and x-ray density values are ~8.35 Å and 5.347 g/cm^3. The coercive field (H_c) was observed to be 175.50 Oe. Some initial experiments like laser diffraction from aligned probe particle and magnetic levitation technique also confirmed the good magnetic response behavior of the probe magnetic material [26].

3. Series assembly of fiber-cantilever beam deflection configuration

Here, we aimed at devising a magnetic field sensing set-up which will be sensitive to low magnetic field but purely all-optical configuration with minimum system complexity. We initiated our work towards devising a series assembly of fiber-cantilever beam deflection arrangement. Magnetic field in the vicinity was measured by modulating the amplitude of the propagating light through optical fibers utilizing induced magnetization of the probe sample in a magnetic field. In the following, the experimental configuration is described followed by the theoretical model to interpret the experimental results.

3.1. Experimental details and results

Cobalt-doped nickel ferrite nanoparticles coated optical fibers were used as cantilevers for the detection of magnetic field in a cantilever beam deflection set-up (Fig. 1). By the term “series assembly of fiber-cantilever”, we describe a configuration that involves two successive transverse misalignment zones in a series arrangement unlike the single-cantilever scheme where only a single misalignment zone was present. We launched He-Ne laser light (632.8 nm) into one port of an input fiber (fiber 1) with the help of coupling unit and other port was kept fixed on a stage. Two end ports of the second fiber were coated with probe magnetic material and placed head-on with respect to first input fiber and third receiving fiber using two three dimensional translational stages by

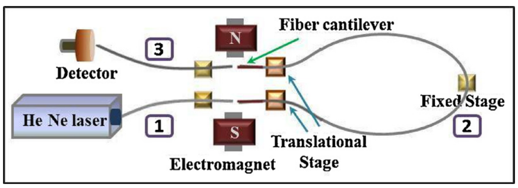

Fig. 1. Schematic of series assembly of fiber-cantilever configuration.