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A deflection optical sensor based on a Scotch tape waveguide with an integrated grating coupler

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ABSTRACT

A deflection sensor based on a plastic waveguide cantilever is presented and demonstrated. The waveguide cantilever is made of conventional adhesive tape and integrates a metal grating coupler at its deflecting end. Light impinging the grating is coupled into the tape waveguide and guided to a fixed photodetector on which the opposite end of the waveguide is anchored. The photodiode acts as the cantilever support and converts guided optical power into a photocurrent (sensor response). Deflection optical monitoring relies on the variation of the overlap of the incident light beam spot with the grating coupler as a function of the cantilever deflection. This approach leads to a larger deflection sensitivity than that obtained by a method based just on the variation of the grating coupling efficiency with the incidence angle. A 14.85-mm-long cantilever sensor has been fabricated and exhibits a linear working range of 2 decades with a maximum deflection sensitivity of 0.2 μA/μm and a resolution of 1.7 μm, limited by the interrogation light source noise. Noise analysis indicates the feasibility of sub-nanometric deflection resolution.

1. Introduction

A cantilever is a mechanical device that can work as a physical, chemical or biological sensor by monitoring variations in its bending or vibration frequency [1]. Particular sensing uses of cantilevers are numerous and include the detection and/or monitoring of pressure [2], force [3,4], mass [5] biomolecules [6], temperature [7], magnetic field [8], displacement [9], strain [10] and acceleration [11]. Although many of these applications employ cantilever sensors having micrometric or nanometric dimensions (micro/nano cantilevers), sensing configurations using several-millimeters long cantilevers, mainly based on glass or plastic optical fibers, have also found great applicability [10,11].

To measure cantilever deflection, electrical [2,5,8] and optical [12–17] methods are typically employed. Optical schemes are particularly appealing because they offer high resolution and immunity to electromagnetic interference. These methods include optical beam deflection (OBD) [12], interferometry [13], interdigitated transducer deflection [14], waveguide coupling [15], integrated Bragg grating [16] and diffraction grating coupling [17]. All these techniques have pros and cons and the use of a given scheme depends on particular implementation and application issues such as resolution, operating conditions, available technology and system size and cost.

In this work, a cantilever sensor based on an alternative optical approach for measuring deflection is presented. The device operation relies on the amount of optical power coupled to a cantilever waveguide through an embedded grating coupler (GC) as a function of the cantilever deflection. Unlike previous devices based on a GC integrated in an optical waveguide cantilever [17], deflection monitoring is not mainly related to changes in the incidence angle of an exciting light beam, but to the variation of the overlap of the interrogation light beam spot area with that of the GC as the cantilever deflects. The technique is demonstrated and analyzed by implementing and characterizing a several-millimeters long optical cantilever based on a recently demonstrated Scotch tape waveguide with an embedded metal GC [18,19]. The sensor includes an encapsulated photodiode that acts as both, light detector and support for the cantilever, which is also a novelty as compared to previous optical cantilever schemes. Noise contributions in the fabricated sensor configuration are also analyzed in

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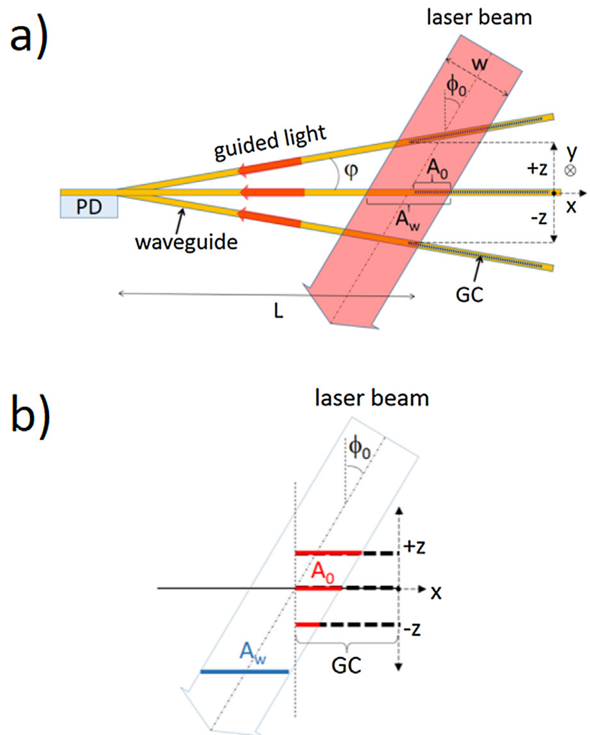

Fig. 1. a) Schematics of the proposed tape waveguide cantilever deflection sensor with an integrated metal grating coupler (GC) in the deflecting tip. The waveguide is anchored onto a fixed photodetector (PD). b) Simplified scheme for small deflection angles (|z| < <L). Parallel red lines indicate laser beam overlap with the GC for different values of z.

order to investigate the feasibility of deflection resolution improvement.

2. Principle of operation

Fig. 1a shows a two-dimensional (i.e., invariant along y-axis) schematic diagram of the proposed optomechanical sensing configuration. It consists of a slab waveguide cantilever anchored to the active surface of a photodetector (support) at one end. The opposite waveguide end is the moving tip and contains an integrated GC. The cantilever length (L) is defined as the distance from the GC edge closer to the photodiode to the photodiode edge closer to the GC. When a laser beam illuminates the deflecting tip, a part of the impinging light is coupled to the waveguide via the GC and guided to the photodetector. The latter provides a photocurrent (i_p), proportional to the received optical power. Note that the laser beam is partially misaligned with the GC such that a fraction (f) of the beam cross-section (w) illuminates the GC. This fraction depends on the cantilever deflection (z) and the angle of incidence of the laser beam for zero deflection (ϕ_0), that is, $f(z,\phi_0) = W(z,\phi_0)/w$, where $W(z,\phi_0)$ is the beam cross-section illuminating the GC.

Optomechanical cantilevers operate typically at small deflection angles (φ), that is, deflection is much smaller than the length of the cantilever. Curvature and tilt effects can therefore be neglected for the calculation of $f(z,\phi_0)$ by assuming that the GC moves along the z-axis, parallel to the x-axis for any small deflection value, as schematized in Fig. 1b. Thus, from Fig. 1b:

$$f(z,\phi_0) = \frac{(A_0 + z \cdot tan\phi_0)}{\left(\frac{w}{cos\phi_0}\right)} = \left(\frac{A_0}{A_W}\right) + \left(\frac{tan\phi_0}{A_W}\right) z, \ for \ \left(\frac{-A_0}{tan\phi_0}\right) \leq z \leq \left(\frac{A_W - A_0}{tan\phi_0}\right) \quad (1)$$

where A_W and A_0 are the projection sections on the x-axis of w and $W(0, \phi_0)$, respectively (Fig. 1). Using Eq. (1), the photocurrent can be written as a function of the cantilever deflection as:

$$i_p = \Re P_p = \Re \eta_p \eta_G (z,\phi_0) [\exp(-\alpha L)] P_i \left[\frac{A_0}{A_W} + \left(\frac{tan\phi_0}{A_W}\right) z\right] = F(z,\phi_0) \cdot f(z,\phi_0), \ for \ \left(\frac{-A_0}{tan\phi_0}\right) \leq z \leq \left(\frac{A_W - A_0}{tan\phi_0}\right) \quad (2)$$

where $\Re$ is the photodiode responsivity, P_p is the optical power absorbed in the photodiode, η_p and $\eta_G(z,\phi_0)$ are the coupling efficiencies for the photodiode and GC, respectively, α is the waveguide loss coefficient, L is the waveguide length and P_i is the incident laser beam optical power. It is assumed that η_G is a function of the angle of incidence $\phi = \varphi + \phi_0$, with $\varphi = \arcsin(z/L)$. Factor $F(z,\phi_0)$ has been introduced for convenience as will be seen in Section 4. Thus, the deflection sensitivity would be:

$$S_z = \frac{\partial i_p}{\partial z} = \left(\frac{A_0}{A_W}\right)\left(\frac{\partial F}{\partial z}\right) + \left(\frac{tan\phi_0}{A_W}\right) \left[z\left(\frac{\partial F}{\partial z}\right) + F(z,\phi_0)\right], \ for \ \left(\frac{-A_0}{tan\phi_0}\right) \leq z \leq \left(\frac{A_W - A_0}{tan\phi_0}\right) \quad (3)$$

3. Experimental

A Scotch tape waveguide with an integrated metal stripe GC was created as described in [18]. Briefly, a 1.2 mm × 1.2 mm 500-nm-period GC, consisted of 270-nm-wide and 100-nm-thick Al stripes, was first fabricated on a polycarbonate substrate [20] and transferred to a 50-μm-thick Scotch tape (#550 Scotch®, 3M, St. Paul, MN, USA) by a simple *stick and peel* method [21], the stripes being normal to the tape length direction. Then, the GC was embedded between two tapes by the adhesion of another piece of Scotch tape onto that containing the GC. Finally, the resulting double-tape configuration was cut with a scalpel to obtain a 19.85-mm-long and 2-mm-wide waveguide embedding the metal GC in one of its ends.

A waveguide cantilever was created by attaching the GC-free tip of the tape waveguide onto the active surface of a p-i-n Si photodiode (OSRAM Opto Semiconductors, BPW 34, Regensburg, Germany), which acted as the fixed support for the cantilever. The tip-photodiode attachment was achieved such that the tip end was aligned with the center position of the photodiode active area in order to obtain the highest waveguide-photodiode in-coupling efficiency [19]. The resulting cantilever length, as defined in the previous section, was L = 14.85 mm. The waveguide end containing the GC was used as the deflecting (sensitive) part of the cantilever. Fig. 2a shows a photograph of the fabricated sensor configuration.

Fig. 2b depicts a schematic diagram of the waveguide cantilever characterization set-up. The photodiode was connected in series to a resistor (R = 910 Ω) and reverse biased to operate in photoconductive mode. The voltage drop in the series resistance (sensor response) was monitored with a 100-nV resolution multimeter (Hewlett Packard 3478A). A 635-nm-wavelength laser diode (World Star Tech TECRL-635) was employed to illuminate the GC at different angles of incidence. A 20 × objective of focal length (FL) = 10 mm was used to both, focus the laser beam onto the GC to a spot size (w) of approximately 60 μm and control the angle of incidence. A linear polarizer was employed to TM (E-field perpendicular to Al stripes) polarize the light beam impinging the GC. The total optical power hitting the GC was measured to be P_i = 7.9 mW. The cantilever tip was deflected by mechanical pushing along the z-axis with a metal needle attached to a micrometer positioning linear stage, used to measure the applied deflection. The distance from the pushing point to the GC edge closer to the photodiode was x_d = 3.5 mm (Fig. 2b). Therefore, for small deflection angles (|z| « L),