High Sensitivity Polymer Optical Fiber-Bragg-Grating-Based Accelerometer

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***Abstract*— We report on the fabrication and characterization of the first accelerometer based on a polymer optical fiber Bragg grating (FBG) for operation at both 850 and 1550 nm. The devices have a flat frequency response over a 1-kHz bandwidth and a resonance frequency of about 3 kHz. The response is linear up to at least 15 g and sensitivities as high as 19 pm/g (shift in resonance wavelength per unit acceleration) have been demonstrated. Given that 15 g corresponds to a strain of less than 0.02% and that polymer fibers have an elastic limit of more than 1%, the polymer FBG accelerometer can measure very strong accelerations. We compare with corresponding silica FBG accelerometers and demonstrate that using polymer FBGs improves the sensitivity by more than a factor of four and increases the figure of merit, defined as the sensitivity times the resonance frequency squared.**

***Index Terms*— Accelerometer, fiber Bragg grating, optical fiber sensor, polymer optical fiber.**

I. Introduction

FIBER Bragg grating (FBG) sensors have attracted a lot of attention in the last decade because of their performance, size, and multiplexing capability [1]–[3]. Traditionally, silica FBGs were used because of their low loss and high operational temperature. However, polymer optical fiber (POF) FBGs have also recently been used in order to exploit the low Young's modulus (2-3 GPa compared to 72 GPa of silica [4]), and high failure strain (up to 10% [3], [4]). FBGs in POF were developed for various resonance wavelengths [3], [5]–[9]. In particular, there has been interest in FBGs with a resonance wavelength (λ_B) of 850 nm [8], [9] where POFs have much lower loss than around 1550 nm and where CMOS components are available. FBGs-based sensors have the advantage of being easy to multiplex, which has now also been demonstrated for POF FBGs [10], [11] thereby enabling temperature compensation [11]. Most POF FBGs are made of Poly(methyl methacrylate) (PMMA) but recently humidity insensitive POF FBGs in TOPAS were also developed [12], [13].

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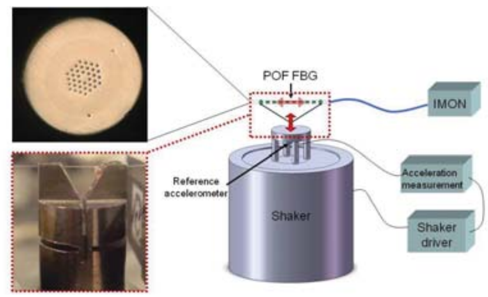

Fig. 1. Schematic of the accelerometer characterization setup. Top inset: mPOF cross section. Bottom inset: mPOF FBG-based accelerometer.

Fiber optic accelerometers [14], which are insensitive to electromagnetic interference and able to withstand harsh environments, can be used where conventional piezoelectric accelerometers would fail [15]. They have been based on interferometric techniques [14], [16]–[18], intensity change detection [19] and FBGs. The first demonstration of an FBG-based accelerometer was made by Berkoff et al. [20] and since then many different designs have been adopted [21], [22] and various performances in terms of sensitivity, frequency response, and signal to noise ratio have been achieved [18].

Here we present the development and characterization of the first POF FBG based accelerometers for operation at both 1550 and 850 nm. Corresponding accelerometers based on silica FBGs are used for a comparative performance evaluation [23].

II. Accelerometer Concept and Realization

The basic construction of the fiber-optical accelerometer is shown in Fig. 1. The acceleration is converted into strain by a mechanical transducer (Brüel & Kjær). The transducer has a fork shape and acceleration causes an increase in the separation between the arms of the fork. The FBG is attached to the fork and is then elongated. In FBGs, elongation produces a wavelength shift ($\Delta\lambda_B$) proportional to the strain (ε): $\Delta\lambda_B = 2n_{eff}\Lambda_B\varepsilon$, where n_{eff} is the effective refractive index and Λ_B is the grating period. The transducer is made so that the strain on the fiber is linearly dependent on acceleration. In this way the Bragg wavelength shift corresponds to acceleration [23]. The POF FBGs were produced by using the phase mask technique and a 30 mW 325 nm CW HeCd laser (IK5751I-G, Kimmon). The phase masks (Ibsen Photonics) have a pitch of 1024.7 nm for the 1550 nm FBGs and a pitch of 572.4 nm for the 850 nm FBGs. The POF in the accelerometer is a three ring microstructured POF (mPOF) made of PMMA with a hole diameter to pitch ratio of about $d/\Lambda = 0.5$ (top inset

Fig. 1). This is above the threshold of $d/\Lambda = 0.42$, which ensures endlessly single-mode operation of microstructured optical fibers of arbitrary base material, and thus our mPOF is few-moded [9].

A 40 cm mPOF with a 5 mm FBG (cleaved at 77.5 °C [24]) was glued onto the 10 mm fork of the Brüel & Kjær designed transducer (lower inset Fig. 1) and then butt coupled to a silica SMF 28 and glued to it for stability. The gluing process is important for the linear operation of the accelerometer. A first bonding (silica-PMMA) with an optical UV curable glue (NOA78-Norland) was made in order to have index matching between the fibers and to avoid Fabry–Perot cavity effects. This glue has poor mechanical strength, so a second UV curable glue was used to make the bonding stable. The mechanically stable glue was also used to fix the FBG onto the transducer. At first the fiber at one end of the grating was fixed on one of the transducer arm. After applying the desired pretension, the fiber at the second end was then glued on the second arm.

The test setup is shown in Fig. 1. A current driven shaker (Brüel & Kjær Type 4810) provides acceleration levels up to 15 g at frequencies up to 18 kHz. The mPOF FBG accelerometer is placed on top of the shaker platform. Underneath we placed a piezoelectric accelerometer with integrated charge preamplifier (Brüel & Kjær 4507) as a feedback reference for the current generator, in order to ensure that the shaker produced the desired acceleration level. The Bragg peak shift is measured with an I-MON 850-FW interrogator for 850 nm operation and an I-MON 80D-R interrogator for 1550 nm operation (both from Ibsen Photonics). The experiments were conducted at about 23 °C in an air conditioned room to limit the Young's modulus temperature dependence. Thus this factor should be taken into consideration by specific mechanical test on the different fibers. Several mPOF FBGs were written with resonance wavelengths around 850 nm and 1550 nm (also different fiber thickness have been used) and FBGs in silica fibers with the same resonance wavelengths were used for comparison. Both the wavelength shift versus acceleration at a fixed frequency and the wavelength shift versus frequency at a fixed acceleration were characterized.

III. Acceleration Measurements

In order to test the sensitivity and operational range of the accelerometer, the response to a sine wave with a fixed frequency of 159.2 Hz was measured. The amplitude of the excitation is proportional to the acceleration and accelerations in the range from 0.1 g to 15 g (RMS) was used for the measurements shown in Fig. 2. In order to analyze the results we first investigate the influence of the fiber diameter on the sensitivity. To do so we compare in Fig. 2 the response of an accelerometer based on an 850 nm FBG in two mPOFs with an outer diameter (OD) of 160 μm (solid red line) and 130 μm (solid blue line), respectively. The sensitivity is, as expected, lowest for the accelerometer using a thick fiber, simply because a larger cross-sectional fiber area translates into a higher spring constant. Here the sensitivity drops from 5.9 pm/g to 4.22 pm/g with the 30 μm increase in OD. With the influence of the fiber diameter in mind we can now compare the sensitivities of corresponding polymer and silica FBG accelerometers. The black solid and dashed lines show the response of a 1550 nm FBG accelerometer using a 130 μm OD mPOF and an 80 μm OD silica fiber, respectively. Both show a linear response in the whole measurement range of 0.1-15 g, but the sensitivity of the mPOF accelerometer is about 3 times higher than the corresponding silica fiber accelerometer (15.2 pm/g against 5.1 pm/g), despite that the mPOF has a 50 nm larger diameter. The same improved sensitivity is found for the FBG accelerometer operating at 850 nm, where the 130 μm OD mPOF gives a sensitivity of 5.9 pm/g (solid blue line), which is 3.3 times the sensitivity of 1.8 pm/g obtained with a thinner 125 μm OD silica fiber (dashed blue line).

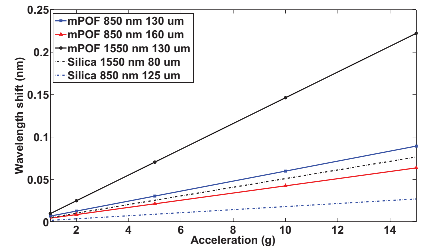

Fig. 2. Bragg wavelength shift versus acceleration for accelerometers based on silica FBGs with resonance wavelength of 1550 nm (80-μm OD, dashed black line) and 850 nm (125-μm OD, dashed blue line) and mPOF FBGs with resonance wavelength of 1550 nm (130-μm OD, solid black line) and 850 nm (solid blue line for 130-μm OD and solid red line for 160-μm OD).

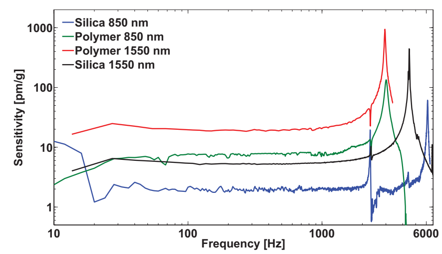

Fig. 3. Frequency response of the accelerometers normalized to the applied acceleration of 1 g. Fiber and accelerometer data are given in Table I.

From Fig. 2 we also observe that the sensitivity decreases when the Bragg wavelength decreases, which is seen for both the mPOF and silica fiber based accelerometers. This is a well-known effect basically due to the fact that the same elongation is transduced to a wavelength shift proportional to the resonance wavelength [9].

The responses shown in Fig. 2 are limited to 15 g because of the shaker limit. It is important to note that this corresponds to a wavelength shift of less than 300 pm and a strain of less than 0.02%. Given that the linear response regime of polymer fibers is much higher, then it is evident that the mPOF FBG accelerometer can measure very high accelerations.

IV. Frequency Response

In Fig. 3 we show the frequency response for a fixed acceleration of 1 g for 1550 nm and 850 nm operated FBG accelerometers based on mPOF and silica FBGs. The response has been normalized to the applied acceleration and FBG and

TABLE I
*MEASURED AT FIXED ACCELERATION, i.e., 1 G, AND CALCULATED AS THE AVERAGE OF THE FLAT PART OF THE FREQUENCY RESPONSE

Material	λ_B [nm]	OD [μm]	Sensitivity* [pm/g]	f_{res} [kHz]	FOM [$10^6 Hz^2 pm/g$]
PMMA	1550	130	19	2.9	159.79
PMMA	850	130	7.6	3	68.4
Silica	1550	80	5.3	4.4	102.608
Silica	850	125	1.8	6.1	66.978

accelerometer data are summarized in Table I. For all the FBGs, the accelerometer shows a flat response for frequencies up to about 1 kHz. When using a silica FBGs the resonance frequency (f_{res}) is higher because of the stiffness of the fiber. A more compliant fiber, such as the mPOF, lowers the system resonance frequency. The resonance frequency is close to 3 kHz for both mPOF based accelerometers, while it is 4.4 kHz when using the 80 μm OD 1550 nm silica FBG and 6.1 kHz for the 125 μm OD 850 nm silica FBG.

The two mPOF FBG based accelerometers have the same resonance since they use the same fiber. while the silica FBGs are written in two different fibers. The thicker fiber shows a higher resonance because of the system being stiffer. The positive side is that a more compliant fiber has a higher sensitivity. In fact it is possible to see that the mPOF based accelerometers have a sensitivity about four times higher than the corresponding silica based ones. In order to take into account both factors a figure of merit is often used when characterizing accelerometers, which is the product of the sensitivity and the square of the resonance frequency. A comparison between silica and polymer fiber based FBG accelerometers is given in Table I, from which we see that the sensitivity gained by using polymer fibers, because of their about 30 times lower Young's modulus, compensates for the decrease in resonance frequency, and gives the polymer FBG accelerometer the highest figure of merit.

It must be considered that for this particular figure of merit, an increase in thickness of the fiber would in fact give an advantage since the gain in resonance frequency counts more than the gain in sensitivity (for example in the 850 nm accelerometers the difference in figure of merit between polymer and silica is lower than for the 1550 nm ones because the fiber is thicker). In any case, the choice of the accelerometer is often given by the particular application for which it is intended. Disregarding the resonance frequency and looking only at frequencies lower than 1 kHz, then the mPOF FBG based accelerometers have better performances than the silica ones for both 850 nm and 1550 nm operation.

In conclusion we demonstrated the first mPOF FBG based accelerometer operating at both 850 nm and 1550 nm. We characterized the accelerometers and demonstrated that they have a linear response (at 159.2 Hz) for accelerations up to 15 g and a flat frequency response up to 1 kHz with a resonance frequency around 3 kHz for a fixed acceleration of 1 g. The polymer FBG accelerometers were compared to identical accelerometers based on silica FBGs. The results showed that the use of polymer FBGs increased the sensitivity by a factor of about 4 and improved the figure of merit, given by the sensitivity times resonance frequency squared.

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