

High frequency vibration sensor using a fiber laser with a multicore fiber interferometer

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Abstract— We present an interferometric vibration sensor that uses 3-core fibers. The transducer is constructed by splicing a segment 20 mm long of a multicore optical fiber (MCF) to a single-mode optical fiber (SMF). The end of the MCF segment is cut off and painted using silver metallic paint. The sensor head is operated in reflection mode. The structure is placed on a PVC plate which is excited with a wide range of frequency signals. The vibrations induce cyclic bending in the MCF segment, resulting in periodic oscillations of the reflected interference spectrum. This device is demonstrated to be suitable to measure vibrations in a frequency range of the order of 300 kHz detecting deformations as small as 0.40 μm .



Index Terms— Vibration, multi-core optical fiber, interferometer

I. INTRODUCTION

VIBRATION analysis play an essential role in ultrasonic medical diagnostics [1]. In the automotive industry, vibrations are studied to evaluate components such as bearings and exhaust systems [2]. It is a complex process involving the evaluation of a wide variety of frequency ranges [3]. This complexity is closely related to both the inherent structure and the most relevant vibration modes [4], [5]. Given the many applications and broad spectrum of interest, a wide variety of sensors (also called accelerometers) have been developed.

The use of optical fibers to monitor vibrations offers several significant advantages, such as their immunity to electromagnetic interference and corrosion, their long-distance interrogation capability, and their inherent flexibility, among others [6]. These advantages have driven the optical fiber based vibration sensors to a high development level [7], [8].

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There are several approaches to detect vibrations using optical fibers, such as Fabry-Pérot interferometers, fiber Bragg gratings (FBG) [7], [9], as well as multicore fiber interferometers (MCF) [10], [11]. The design of MCF fibers can be classified as weakly and strongly coupled. In the first case, the cores are typically far apart, reducing the coupling between them and increasing the mode beating length. The second group instead, leads us to a stronger coupling and shorter beating lengths.

Given the maturity reached by the Bragg grating technology, many sensors combine FBGs inscribed over weakly coupled multicore fibers [12], [13]. The usual applications of such sensors are to monitor curvature, bending or shape [2], [10]. Their main advantage is their ability to distinguish the direction of curvature to achieve 3D shape detection with a single MCF. However, a disadvantage of MCF cores containing Bragg gratings is the need for expensive input/output coupling devices to interrogate each core individually.

With a similar approach, some MCF-based vibration sensors have been reported in recent years. *TABLE I* presents a review of interferometer-based vibration sensors. The results indicate that the interferometric vibration sensors based on MCF can provide a wide frequency measurement range, ranging from 1 mHz [14] to 12 kHz [15]. The maximum experimentally measured frequency is 12 kHz, while the maximum theoretically measured frequency is 25 kHz.

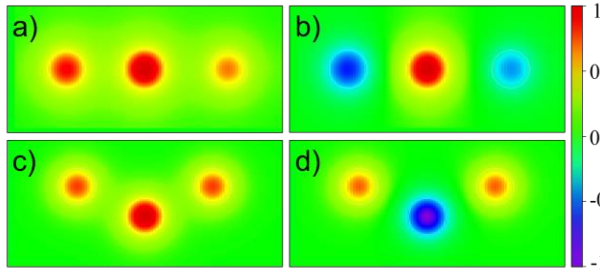


Fig. 2 Normalized field distribution of the (a) fundamental and (b) second order supermodes of the in-line multicore structure. (c) and (d) show the same supermodes for the V arrangement.

A fully vectorial finite difference mode solver has been used for the analysis of the multicore fibers. Fig. 2 shows the symmetric field distribution of the fundamental and second order LP₀₁ supermodes for both in-line and V arrangements. The first-order asymmetric mode is omitted because the mode of the SMF fiber does not excite it. In fact, the symmetric supermodes carry nearly all the power, with 54% for the fundamental mode and 46% for the second order mode. The propagation analysis shown in Fig. 3 over 40 mm provides a beat length or around 18 mm for the in-line multicore configuration and 30 mm for the V arrangement.

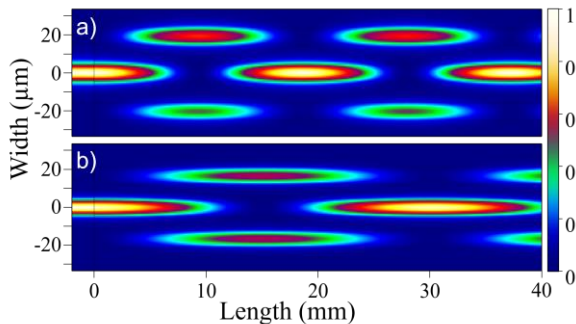


Fig. 3 Intensity distribution along 40 mm in the a) in-line and b) V-arrangement multicore fibers excited by a standard singlemode fiber.

Using a high-resolution optical backscatter reflectometer (LUNA OBR 4600), we conducted an analysis of the reflected power from both in-line and in V structures, obtaining the reflection spectrum for lengths of 30 cm and 50 cm, respectively. Fig. 4 a), shows the central core's power coupling in and out to the sides 6 times every 10 cm, to provide an estimated coupling length of 16 mm. The same phenomenon can be observed in Fig. 4 b) for the V arrangement, where the coupling length is approximately 28 mm. Both results are in good agreement with the theoretical calculations.

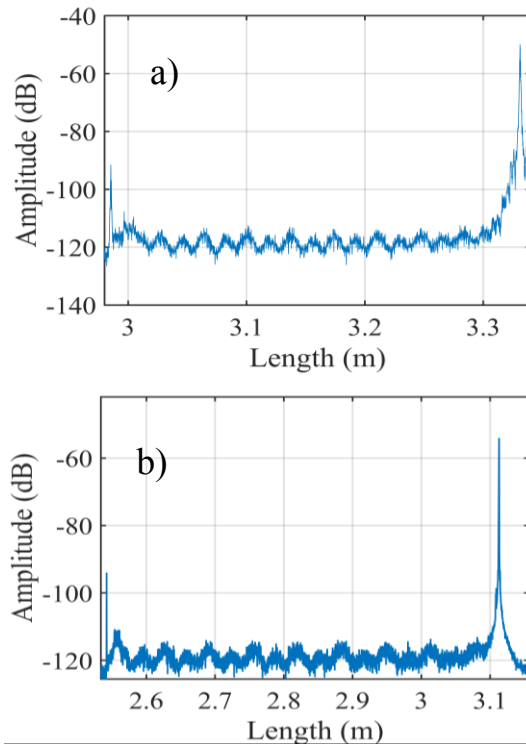


Fig. 4 Backscattered optical power as a function of fiber length from a) 3-core in-line fiber, 30 cm and b) 3-core in-V fiber, 50 cm fiber. Measurements carried out using an OBR (4600 from Luna).

The sensor fabrication was carried out by splicing a 20-mm segment of 3-core MCF to a single-mode fiber, as shown in Fig. 5 a). A silver-painted mirror was applied at the right end of the MCF segment (indicated as M). A Fujikura FSM-100p+ fusion splicer was used to splice both elements. Fig. 5 b) shows a photo of the fusion between the MCF and SMF segment, captured using the built-in fusion splicer's microscope. During the manufacturing process a very efficient coupling between the SMF and the MCF was achieved, resulting in a low insertion loss. By carefully adjusting the splicing process, we achieve losses, as low as 0.01 dB.

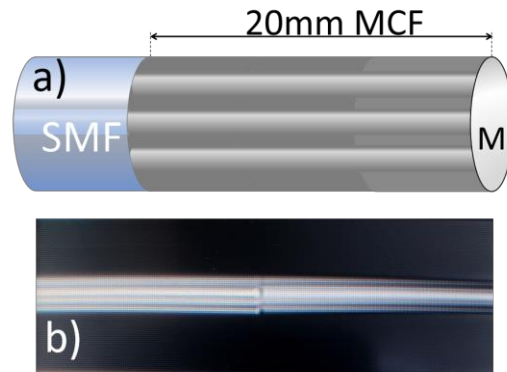


Fig. 5 a) Sensor structure: SMF (single mode fiber), MCF (multicore fiber), mirror (M). b) Photograph of the MCF sensor taken using a Fujikura 100P fiber fusion splicer.



In our design, the sensor was placed on the edge of a PVC plate, exposed to the controlled motion of a Mechanical Wave Controller SF-9324. It was excited with a sine wave provided by an HP33120A signal generator. The vibration was measured with an electronic commercial sensor (LDT1-028K), placed under the PVC sheet, and taken as a reference, as presented in *Fig. 6*. The photograph shows the experimental setup of the sensor.



Fig. 6 Experimental setup of the sensor to apply the vibration frequency.

As the PVC plate vibrates, it exerts forces on the multicore fiber, causing it to bend cyclically. This bending introduces periodic variations in the fiber's physical structure. When the fiber bends due to the vibrations, it alters the optical path lengths of these cores, affecting the interference patterns.

The vibration causes periodic deformation in the MCF, leading to cyclic changes in the modes of interference and, consequently, periodic changes in the interference pattern [9], [25], [26], [27].

The setup in *Fig. 7* was used to obtain the interference pattern of the structure. A broadband light source (BLS) was injected into the circulator at port 1. The SMF-MCF structure was connected to port 2, and the reflected signal was measured with an optical spectrum analyzer (OSA) connected to port 3 of the circulator.

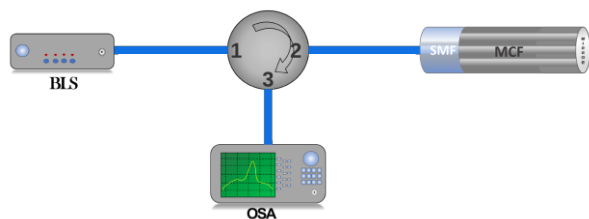


Fig. 7 Experimental setup for the measurement of the interference pattern in reflection.

The resulting optical spectrum response measured by the 0.1 nm resolution OSA and showing the interference pattern is depicted in *Fig. 8*.

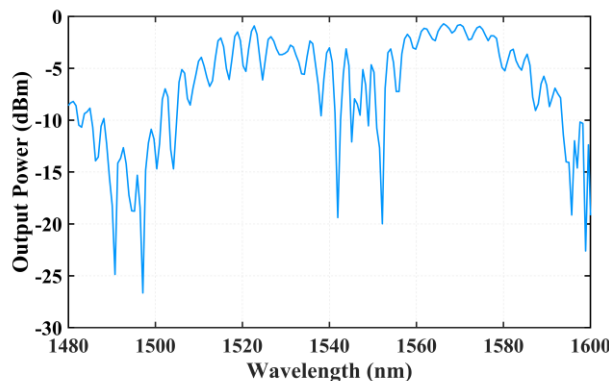


Fig. 8 Reflected optical spectrum of the 20-mm MCF segment measured using an OSA.

III. EXPERIMENTAL SETUP

To interrogate the sensor, the erbium doped linear fiber laser shown in *Fig. 9* was arranged. This structure has already exhibited excellent performance in sensing, as it was reported in [28]. A 980 nm pumping laser is injecting into the linear-cavity fiber laser via the 980/1550 nm wavelength division multiplexer (WDM). The gain medium, located at the 1550 nm port of the WDM, consists of 3.4 meters of erbium-doped fiber (EDF). This EDF used is type I25(980/125), ideal for its use in C-band amplifiers and with a core composition optimized for erbium-doped fiber amplifiers (EDFA) in dense wavelength division multiplexing (DWDM) network systems. The maximum core absorption ranges from 7.7 to 9.4 dB/m at 1531 nm. The linear cavity of the laser terminates at a fiber Bragg grating, which acts as a filter to reflect the 1560 nm wavelength.

The filtered signal traverses the 1500 nm port of the WDM to reach the optical coupler where a 10% of the signal is directed to the OSA and the remaining 90% is injected to the MCF structure.

The photodetector converts the optical signal into an electrical signal for subsequent analysis with an oscilloscope. The system was isolated from external vibrations for the experimental measurement, and temperature compensation was not implemented.

The sensor's characterization was developed at a stable room temperature of 21°C. If the operating temperature of the vibration sensor is expected to change during its operation, temperature compensation can be implemented. To achieve a complete optical solution, we can use the Bragg grating (FBG) present in the experimental setup, which works as a mirror of the laser structure. To measure the wavelength shift of the laser caused by temperature variation in the FBG, it is enough to take a low-frequency measurement using an OSA [29].

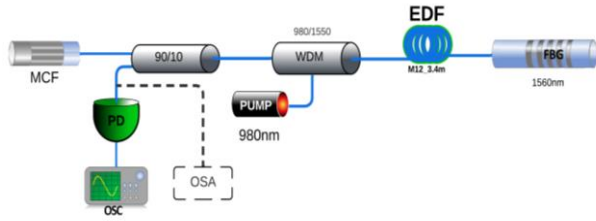


Fig. 9 Experimental setup of the sensor head in the linear cavity laser.

IV. EXPERIMENTAL RESULTS

In Fig. 10 is depicted the optical output spectrum measured with the OSA for the linear cavity configuration, including the MCF structure. A laser peak centered at 1560 nm, with an output power level of -3.36 dBm and an optical signal-to-noise ratio (OSNR) of 24.52 dB was obtained when pumped with 71.53 mW.

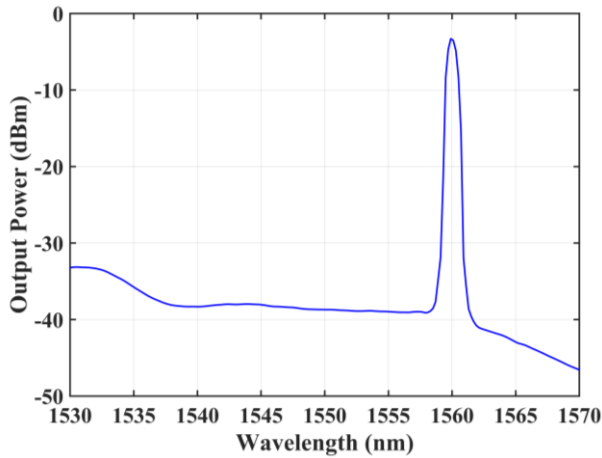


Fig. 10 Output spectrum measured with the OSA for the linear cavity laser configuration including the MCF sensor head.

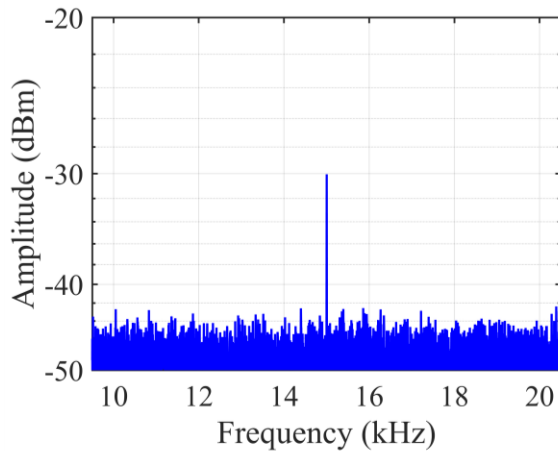


Fig. 11 Frequency response of an electronic commercial sensor, excited with a 15 kHz vibration.

The photodetected signal is processed by using the fast Fourier transform (FFT) to calculate the vibration frequency.

The obtained results are validated by means of the commercial electronic vibration sensor LDT1-028K from Thorlabs. Fig. 11 shows the Frequency response for an excitation frequency of 15 kHz measured with the electronic sensor.

On the other hand, Fig. 12 (a) and (b) show the response obtained using the proposed cavity for two 20 mm fiber fragments with different core distribution patterns (in-line and V, respectively) and for an excitation signal of 15 kHz. It can be observed that the measured spectral response follows the mechanical excitation.

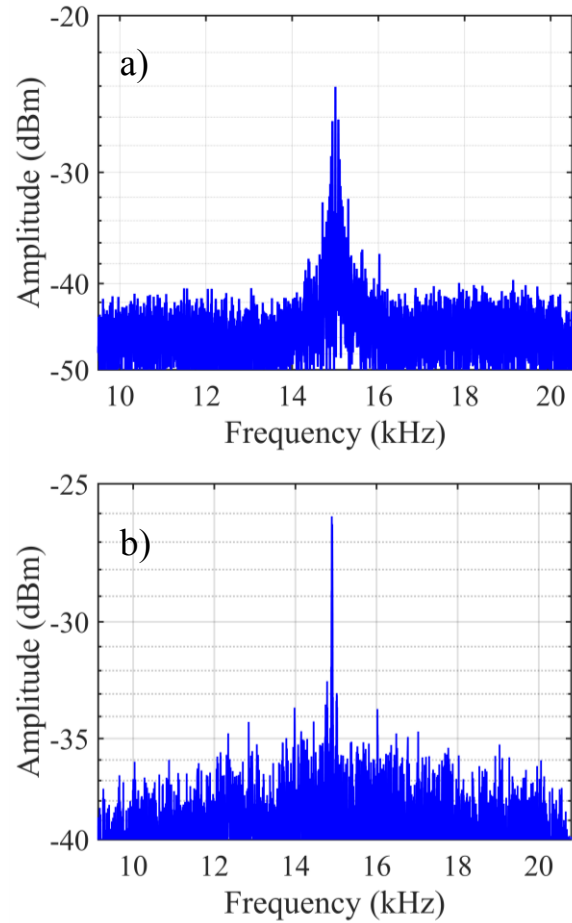


Fig. 12 Frequency response for a 20 mm-long fiber sensor head: a) 3 cores in-line, b) 3 cores in V for an excitation signal of 15 kHz.

The signal measured with the electronic sensor is used as a reference for subsequent measurements, in which a frequency sweep is performed for a better and more accurate characterization of the sensor. The sweep range is established from 10 kHz to 20 kHz with steps of 100 Hz, resulting in the graph shown in Fig. 13. The inset figure amplifies the range between 14 and 17 kHz in which the measurement has a clear linear trend. It is observed that the frequency response of the sensors for the measured range, shows a high linearity. The calculated, coefficient of determination (R^2) for the signals measured with both sensors is very close to 1.

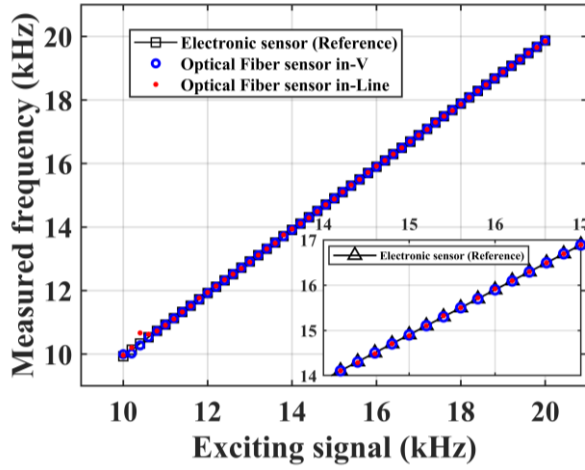


Fig. 13 Excitation signal vs. measured signal, the inset graph shows a close-up of the measured points.

In a second stage of the evaluation process of the fabricated sensors, the setup shown in Fig. 14 was used to excite the sensor in a higher frequency range. It is composed of a piezoelectric PZT shear chip PL5FBP3 that provides a maximum lateral displacement of $1.3\mu\text{m} \pm 20\%$ when driven from -200 V to $+200\text{ V}$. The operation voltage range used for this configuration is $\pm 127\text{V}$, achieving a displacement of approximately the 30% of the maximum range.

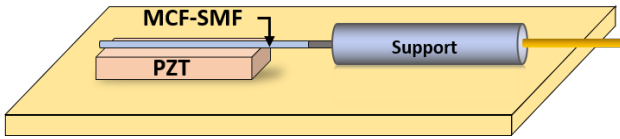


Fig. 14 Experimental setup of the sensing head to apply the vibration frequency of 50-300 kHz using a PL5FBP3 piezoelectric controller.

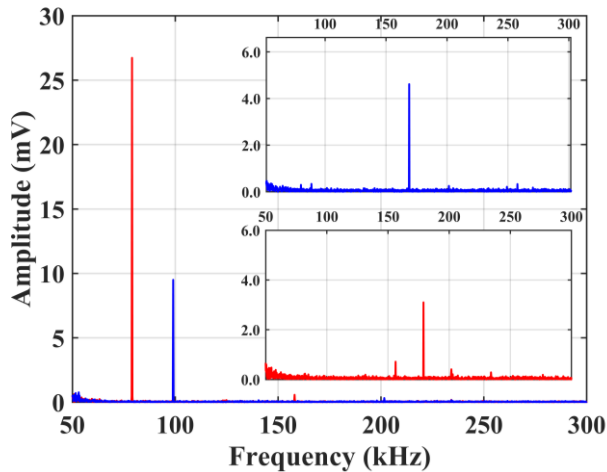


Fig. 15 Frequency response for 3-core in-line (red) and 3-core in-v (blue) fiber-based sensor head for a 50 kHz-300 kHz frequency sweep.

Measuring the setup described in Fig. 9 to interrogate the sensor-head, the PL5FBP3 was excited with frequencies in the

range 80 to 179 kHz. The response of the proposed SMF-MCF structure, and for both in-line and in-V distributions is shown in Fig. 15. The spectra shown in this figure demonstrate that the structure can accurately measure high frequencies with vibration amplitudes as low as $0.40\ \mu\text{m}$.

The Fig. 16 depicts the recorded data for the whole frequency range, measured with a frequency gap of 1 kHz. The inset shows a portion of the spectrum ranging from 130 kHz to 150 kHz in which the excitatory signal points versus measured frequency present a linear tendency.

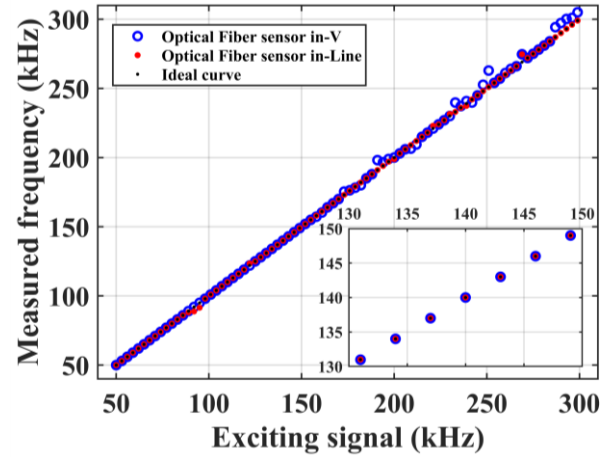


Fig. 16 Excitation signal vs measured signal for both sensing heads.

V. CONCLUSIONS

A vibration sensor has been developed by splicing a short segment of a three-core fiber with a standard single-mode fiber and applying a metallic paint layer at the end of the multicore fiber to achieve high reflectivity. The sensor's manufacturing was carried out using tools and processes standard in the telecommunications industry, which becomes in a cost-effectively solution. In order to achieve a good OSNR in measurements, we have implemented a fiber laser sensing structure, where the three-core fibers transducers act as a mirror of this laser.

It has been demonstrated that this MCF-based interferometric sensor head is highly accurate and reliable for monitoring vibrations in the range of 10 kHz to 300 kHz. The obtained data was compared with those from a reference electronic sensor and the high correlation between both sensors was confirmed, resulting $R^2 = 0.99$. These results surpass the records reported in [16], where a three-core fiber-based sensor was implemented in frequency range up to 20 Hz. This new-type MCF-SMF interferometric sensor is able to accurately measure vibrations in the high frequency range.

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