Sensitivity of an Opto-Acoustic Detector Based on a Modalmetric Interferometer with the Length of Interacting Fibre

Taiane A.M.G. Freitas and Ricardo M. Ribeiro

***Abstract*— This paper describes a simple opto-acoustic detector based on a fibre-optic modalmetric device in reflective structure, primarily thought for digital acoustic communication. A single-mode fibre was spliced with a sensitive multimode fibre (s-MMF) strand leading to a modalmetric device, which was probed with 1550 nm wavelength. A non-linear increase of the phase shift and a higher effective sensitivity of the device were observed when the length of the s-MMF in contact with the surface receiving acoustic signals was increased from 5 to 25 cm, demonstrating enhanced phase sensitivity due multimode interference and the *antenna gain*.**

Keywords* — *Acoustic Communications, Opto-Acoustic Detector, Modalmetric Interferometer, Multimode Fibre.

I. INTRODUCTION

Fibre-optic acoustic sensors, including those based on modalmetric interferometers, provide the advantageous characteristics of optical sensors as: immunity to electromagnetic interference (EMI), large bandwidth, electric isolation and others. It was reported the acoustic communications through a metallic wall using piezoelectric (PZT) transducer as a transmitter and fibre Bragg grating (FBG) as a detector by means of differential detection using PSK modulation [1]. It is recognized that interferometric and FBG sensors may present comparable or even larger sensitivity than of the PZTs [2,3]. The latter usually present few cm^2 of useful sensitive area. A typical multimode fibre with 62.5 μm core diameter should have 1.6 m length to cover only 1 cm^2 of sensitive area. However, an optical fibre is flexible and can be coiled or shaped to a surface where acoustic signals are arriving. As an example, s-MMFs may be coiled around the perimeter of a metallic cable to detect the arrival of an acoustic signal. Therefore, in many circumstances a (sensitive) fibre may be more adaptable than a PZT. Moreover, since a fibre-based device is used for sensing, it is well known that their sensitivity may be increased when the length of the sensitive fibre is also increased, what is commonly called as *antenna gain* [4].

Reflective modalmetric (R-MMI) devices are fibre-optic structures that behave like a multimode one-arm interferometer and have been used as a distributed disturbance detector operating in the electrical frequencies or optical domains [5-7]. This type of device is of simple construction, while retaining other features of fibre-optic sensors such as high sensitivity, immunity to electromagnetic interference, etc.

This paper shows the *antenna gain* on the sensitivity of the lumped & reflective modalmetric devices for optical detection of acoustic signals, i.e. when the interaction length of the sensitive multimode fibre (s-MMF) is increased. Additionally, the multimode nature of the interference enhances the phase sensitivity as compared with two-path interferometers.

II. EXPERIMENTAL

Figure 1 depicts the experimental set-up. The light source was a continuous wave 1550 nm laser with 100 kHz linewidth. The light is launched at the port 1, exits at port 2 of an optical circulator and probes the modalmetric structure itself. A single-mode fibre (SMF) was spliced to a sensitive multi-mode fibre (s-MMF) [8]. The modalmetric interferometer detector operates in the reflective mode (R-MMI). The end of s-MMF was simply cleaved, not *mirrored*. The used SMF and MMF were both of standard Telecom-grade. The reflected signal at ~ 250 μW optical power level, modulated (or not) by the acoustic waves, is recovered by the port 3 of the circulator and impinges the pre-amplified PIN photo-diode followed by an electrical band-pass filter (EBPF) centred at 50 kHz. The pre-amplifier was set at 30 dB (4.75 x 10^4 Ω) transimpedance gain level for high impedance input load, corresponding to 775 kHz bandwidth. The filtered output signals were displayed and recorded in a 100-500 MHz bandwidth 2-5 GSa/s sampling rate digital oscilloscopes.

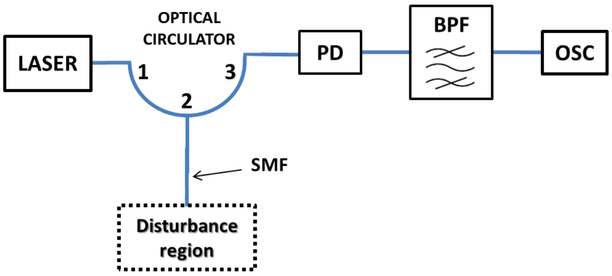

Fig. 1. The experimental setup.

Figure 2 shows the s-MMFs glued on the surface of a PZT disk. The PZT disk, presents 50 mm and 2.5 mm of diameter and thickness, respectively. The manufacturer specifies (44 ± 3) kHz as the resonance frequency of radial mode. An arbitrary function generator (AFG) directly excites the PZT disc with 0-10 V_{pp} voltage range at 42.9 kHz frequency that matches the effective resonance frequency of the disc. The use of a ceramic PZT discs is suitable to generate acoustic waves due to its low cost, simplicity, and availability. It reasonably reproduces the surface of a real solid physical media used for ultrasonic

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Taiane A.M.G. Freitas, tmenandro@id.uff.br; Ricardo M. Ribeiro, rmr@telecom.uff.br. Departamento. de Engenharia de Telecomunicações, Universidade Federal Fluminense. Niterói, RJ, 24.210-240. Este trabalho foi parcialmente financiado pelo CNPq, Capes e Faperj.

communications where it is expecting the arrival of very weak acoustic signals.

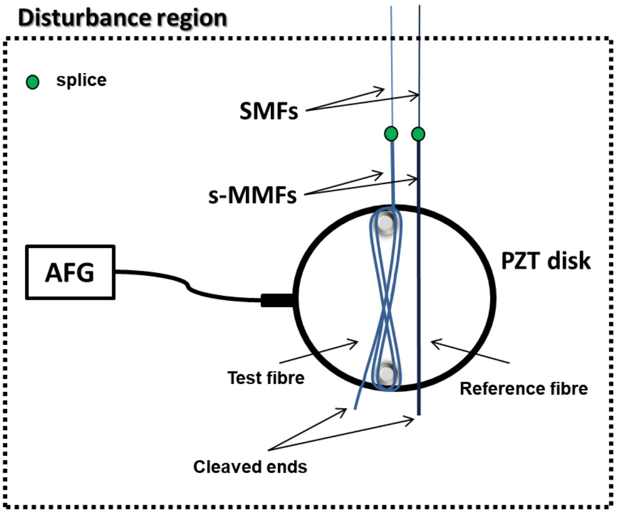

Fig. 2. Scheme of the s-MMFs of different lengths (5 and 25 cm) lying and glued over the PZT disk.

The first s-MMF of 5 cm length is called *reference fibre* whereas the other of 25 cm length is called *test fibre*. The *reference fibre* was simply stretched (0.5 turn) and glued along the 5 cm diameter of the disk. The *test fibre* was bent as a figure-of-eight 2.5 turns loop fitting the 5 cm diameter of the PZT disk and leading to 25 cm total length of s-MMF as is shown in Fig. 2. Both *reference* and *test fibres* were put in contact with the surface of the PZT disk by using a cyanoacrylate based adhesive. However, the device works in reflective mode and as a result the effective interaction length is really the *double* of s-MMF physical length.

III. RESULTS AND DISCUSSIONS

Figure 3 shows the plots of output voltage amplitude (mV) when the input acoustic amplitude V is varied from 0 to 10 V_{pp} for effective interaction length of $2L_{s\text{-}MMF} = 10$ cm and 50 cm. The response of the *reference fibre* ($2L_{s\text{-}MMF} = 10$ cm) is approximately a half-cycle (or ~ 0.5π phase shift) as shown in black squares and the *test fibre* ($2L_{s\text{-}MMF} = 50$ cm) is 4.5 cycles (or 4.5π phase shift) as shown in red circles.

Figure 3 clearly shows that an increase of sensitivity is achieved when the s-MMF of 50 cm effective interaction length was used instead of 10 cm. More precisely in the 0 - 1 V_{pp} range, i.e. low-level excitation, the measured sensitivities are 41 mV/V and 1074 mV/V for the *reference* and *test fibres*, respectively. An increase of 14.2 dB is obtained. For 0-10 V_{pp} range it is also clearly observed the increase of the sensitivity because while for 5 cm s-MMF length, the output exhibit over a half-cycle of an interferometric response, and with 25 cm length an amount of 4.5 cycles is achieved.

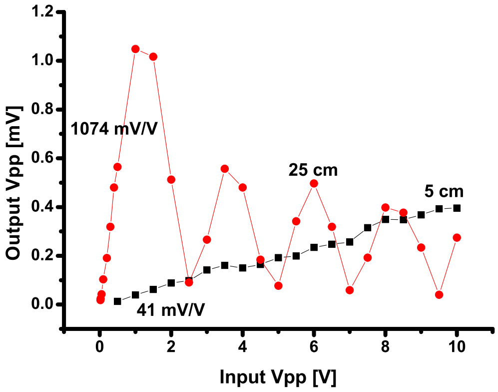

Fig. 3. Output voltage amplitude (mV) dependences with the excitation voltage amplitude (V) applied on the PZT disk.

The sensitivity mechanism of the multimode interference taking place in the s-MMF splice with SMF by excitation with acoustic signals, can be attributed to the induced phase changes of its interfering modes [8]. The mechanism can then be equivalently explained by considering the disturbances as perturbations to the self-image of the input excitation on the output aperture as produced by the multimode interference effect [9]. Thus the index of refraction, length or even the transversal sizes of s-MMF or all of them, are modified by receiving bending or acoustic disturbances. As a result, a corresponding change in the output signal just after the junction of s-MMF with SMF will arise, i.e. occurs a conversion from phase to intensity modulation [9,10].

Calculations were performed for two interfering modes, with the assumption that the phase shift $\Delta\phi$ is linearly dependent with the fibre interaction length $L_{s\text{-}MMF}$, i. e. $\Delta\phi \propto L_{s\text{-}MMF}$ and $\lambda = 1550$ nm. When the acoustic strength is increased the refraction index is also linearly increased by means of the photo-elastic effect, at least for small signals. At first, by setting $2L_{s\text{-}MMF} = 10$ cm the variation of the refraction index was adjusted to reproduce the half-cycle (0.5π) output as was experimentally observed. At second, the calculations were repeated but it was set $2L_{s\text{-}MMF} = 50$ cm instead of 10 cm. As an output, a waveform presenting only 2.5 cycles or 2.5π phase-shift was obtained what is in contrast with the experimental result of 4.5π.

However, the modalmetric device here presented is really a multi-beam interferometer and since the number of interfering modes is three or more, it is expected a higher phase sensitivity as was already demonstrated for a three-arms Mach-Zehnder interferometer [11]. In fact, the comparison of the experimental results with the calculations, suggests that the multimode interferometer may exhibit an enhanced phase-sensitivity when compared with a two-arms interferometer.

Calculations assuming three interfering modes showed that when 0.5π is the output corresponding to $2L_{s\text{-}MMF} = 10$ cm, when $2L_{s\text{-}MMF} = 50$ cm was set, the output could reach 4.5π phase rotations. In all calculations assuming two and three interfering modes, it was assumed the same maximum range of refraction index caused by photo-elastic effect.

Although the sensitivity of the modalmetric device is enhanced when $L_{s\text{-}MMF}$ is increased, their free spectral range and consequently the dynamic range are both shortened. When the acoustic amplitude to be detected increases, the output should not be distorted or attenuated. A high sensitive device is useful for detect very weak signals that may be suitable as a receiver for typical acoustic communications through metallic pipelines, cables or walls [1,12]. Nevertheless, input signals of large amplitudes will produce distorted outputs that can be deleterious even for digital communications using on-off key format.

IV. CONCLUSIONS

For the first time, to the best of our knowledge, this paper showed the *antenna gain* in a modalmetric device. The latter is a lumped opto-acoustic detector (1550 nm) based on the disturbing of the multimode interference that takes place in a reflective SMF-s-MMF spliced structure where the s-MMF is a short section (few centimetres) cleaved at other end. It is intended for digital ultrasonic communications, and not to be a calibrated sensor.

It was observed a non-linear dependence of phase-shift with the interaction length of s-MMF probably due to the interference of three or more modes, and a remarkably increase of the sensitivity. Preliminary calculations are in agreement with this hypothesis. For very weak acoustic disturbance, it was achieved 14.2 dB increase of sensitivity when de $L_{S\text{-}MMF}$ is increased from 5 to 25 cm.

The increase of the s-MMF length in contact with the surface receiving the acoustic signals may be a suitable degree of freedom to increase the sensitivity of the presented device. However, this is accompanied with the decrease of the dynamic range although it is still useful for very weak signals.

REFERENCES

[1] G. Wild and S. Hinckley, “A fibre Bragg grating sensor as a receiver for acoustic communication signals”, *Sensors*, 11, 455-471, 2011.

[2] S. Askkenazi, Y. Hou, S.-W. Huang and M. O’Donnell, “Integrated optoacoustic transducer”, *IEEE Ultrasonics Symposium*, Vancouver, Canada, pp. 864-867, October 2-6, 2006.

[3] M. Moccia, M. Consales, A. Iadicicco, M. Pisco, A. Cutolo, V. Galdi and A. Cusano, “Resonant hydrophones based on coated fiber Bragg gratings”, *Journal of Lightwave Technology*, 30, 15, 2472-2481, 2012.

[4] W. B. Spillman Jr. and D. R. Huston, “Scaling and antenna gain in integrating fiber-optic sensors”, *Journal of Lightwave Technology*, vol. 13, no. 7, pp. 1222-1230, 1995.

[5] J. Park, “Reflection-Type Optical-Fiber Intrusion Sensor Based on Speckle Detection”, *J. of the Korean Physical Society*, 50, 2, 529-531, 2007.

[6] I. Oanca, G.Y. Yang, J. Katsifolis and E. Tapanes, “Simultaneous wavelength multiplexed fiber optic communications and cable integrity monitoring technique”, *CLEO*, paper WP4, 16th July 1997, 106.

[7] E. Tapanes, “Optical Sensors and Method for Producing Fibre Optic Modalmetric Sensors”, WO Patent 96/08695, PCT/AU95/00568, 21.03.1996.

[8] Ricardo M. Ribeiro and Yanes C. Balod, “Modalmetric interferometer under fingerprint disturbances: the effect of lateral offset between the single-mode and multimode fibre splice”, *Microwave and Optical Technology Letters*, 60, 1, pp. 151-157, 2018.

[9] A. Hisham and I. M. El-Sayed, “Monitoring of Vibrations Using Multimode Optical Fiber Sensors”, *33rd National Radio Science Conference* (NRSC 2016), pp. 384-389, Aswan, Egypt, Feb. 22-25, 2016.

[10] J. R. Guzman-Sepulveda, I. Hernandez-Romano, M. Torres-Cisneros and D. A. May-Arrioja, “Fiber Optic Vibration Sensor based on Multimode Interference Effects”, *CLEO Technical Digest OSA*, paper JW2A.117, 2012.

[11] G. Weihs, M. Reck, H. Weinfurter and A. Zeilinger, “All-fiber three-path Mach-Zehnder interferometer”, *Optics Letters*, vol. 21, no. 4, pp 302-304, 1996.

[12] S. Chakraborty *et al*, “Low-power, low-rate ultrasonic communications system transmitting axially along a cylindrical pipe using transverse waves”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 62, no. 10, pp. 1788-1796, 2015.