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An SMS (single mode – multi mode – single mode) fiber structure for vibration sensing

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Abstract. We describe an SMS (single mode - multi mode - single mode) fiber structure to be used in a vibration sensing system. The fiber structure was fabricated by splicing a section (about 300 mm in length) of a step index multi mode fiber between two single mode fibers obtained from a communication grade fiber patchcord. Interference between higher order modes occurs while light from a narrow band light source travels along the multi mode fiber. When the multi mode fiber vibrates, the refractive index profile is changed because of the photo-elastics effect and the amplitude of the interference pattern is changed accordingly. To simulate a vibrating structure we used a loudspeaker to vibrate a wooden table. By using a digital oscilloscope, we recorded and analysed the vibrating signals obtained from the SMS fiber structure as well as from a GS-32CT geophone for referencing. We observed that this SMS fiber structure was potential to be used in a vibration sensing system with a measurement range from 30 to 180 Hz with inherent optical fiber sensor advantages such as light weight, immune to electromagnetic interference, and no electricity in the sensing part.

1. Introduction

To prevent further damage on structures subjected to continuous vibration, monitoring and analysis of vibration that occurs on those structures, such as machines, buildings, and vehicles, are necessary. For this purpose we require sensors to convert physical quantities of vibration (displacement, velocity, and acceleration) into an electrical time-varying signal, hardware to process and record the signal, and software to analyze the signal in time or frequency domain. In this paper, we describe an optical fiber sensor based on an SMS (single mode – multi mode – single mode) fiber structure to be used as a vibration sensor.

Optical fiber sensors have advantages such as immunity to electromagnetic interference, small size, light weight, high sensitivity, and large bandwidth. Fiber interferometers, for example, sense various physical parameters including temperature, strain, pressure, refractive index, and mechanical rotation; it, however, should compete with other already mature technologies in many fields of application [1, 2]. Optical fiber sensors can be placed kilometers away from the monitoring station, because of the intrinsic low optical attenuation of the fiber, and it is also possible to perform multiplexed measurements using arrays of remote point or distributed sensors [3]. Several types of optical fiber sensors such as the Fabry-Perot (FP) cavity, fiber Bragg grating (FBG), and high-birefringence (HB) fiber have been investigated and applied in many areas and, recently, the multi mode interference occurring in an SMS fiber structure has also been studied and developed to act as novel optical devices such as sensors or filters [4]. The advantages of an SMS fiber structure are, among others, high compactness, wide wavelength operation range, low cost, simple to construct, ease of packaging and connection to optical fiber system.

There are several researchers already investigated the use of an SMS structure for vibration measurements. Sun *et al*, for example, employed an SMS structure as a high sensitive optical fiber microphone which can detect human voice within 2 meter range [5]. Wu *et al* used a bent SMS structure for vibration sensing. The bent SMS structure is fixed to a translate stage and a vibration generator. Using an oscilloscope they observed vibration frequencies from 10 Hz up to 1900 Hz [6]. Zhao *et al* demonstrated an SMS structure to measure a vibrating cantilever. Using a lock-in amplifier as a signal acquisition device they obtained sensitivity of 4.741 mV/Hz and measuring range from 2 Hz to 80 Hz [7]. Based on their works, we developed an SMS fiber structure in which the multi mode fiber as the sensing part was coiled on a disc and attached directly on a vibrating structure or platform that would be measured or monitored.

2. Methods

We constructed the SMS fiber structure by splicing a section, about 300 mm long, of a 50/125 step index multi mode fiber (Thorlabs FG050LGA, 0.22 NA) between two 9/125 single mode fibers (Thorlabs SMF-28, 0.14 NA). The multi mode fiber was then coiled on a mini compact disc (diameter: 80 mm) and the whole assembly, acting as the sensing part, was coated with a TFE tape with a total weight is less than 10 grams, see figure 1. As the light source we used a tuneable laser diode (Santec TSL-510, the wavelength is tuned fix at 1560 nm) and for the photodetector we used a Ge photodiode with an adjustable gain amplifier (Thorlabs PDA50B-EC, 0 – 70 dB gain).

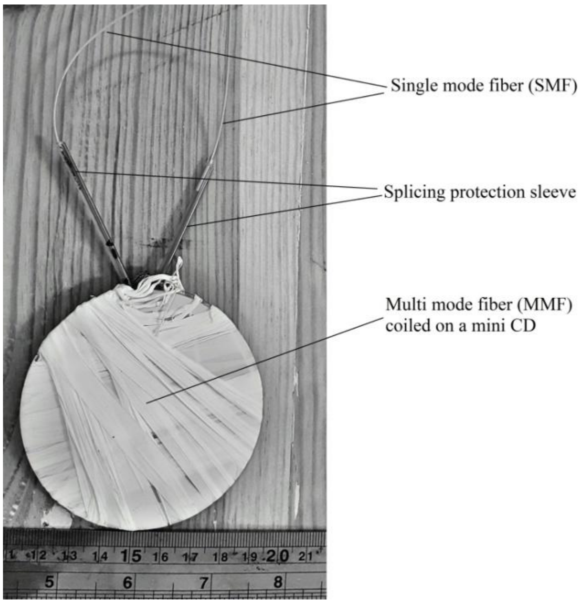


Figure 1. The configuration of an SMS fiber structure for vibration sensing.

When light is coupled from the SMF into the MMF, higher order modes are excited in the MMF and interference between different modes occurs. The relationship between the longitudinal propagation constants for the *m* and *n* order mode can be expressed as [7]:

$$\beta_m - \beta_n = \frac{u_m^2 - u_n^2}{2k_0 a^2 n_{core}} \tag{1}$$

where $k_0 = 2\pi/\lambda$, λ: wavelength of light, a: core radius of the MMF, n_{core}: refractive index of the MMF core, u_m and u_n are the normalized propagation constants: $u_m = \pi(m - ¼)$ and $u_n = \pi(n - ¼)$.

When the phase difference of two modes is the integer multiple of 2π, interference between these two modes occurs when

$$(\beta_m - \beta_n)L = 2N\pi \tag{2}$$

where L is the length of the MMF, and N is a natural number. The wavelength of the constructive interference can be derived as

$$\lambda = \frac{8(2N+1)n_{core}a^2}{(m-n)[2(m+n)-1]L} \tag{3}$$

When the MMF vibrates, the refractive index profile changes because of the photo-elastics effect and the peak of interference pattern will move so that

$$\Delta\lambda = \lambda_N - \lambda_{N-1} = \frac{16n_{core}a^2}{(m-n)[2(m+n)-1]L} \tag{4}$$

and the output light intensity will change accordingly because the deformation of the MMF will lead to the power losses of all the modes, the higher-order modes experience more power loss than the lower-order modes [7, 8].

In our experiment, to excite vibration we used a 6”, 8 Ω, 100 W loudspeaker driven with a low-cost car-audio amplifier. As a signal generator, we used a smartphone with an Android tone generator application. The loudspeaker was used to vibrate a 1 × 1 m^2, 0.5” thick, wooden table. For sensing this vibration we placed the SMS fiber structure nearby the loudspeaker on the table surface side by side with a GS-32CT geophone for referencing. The vibration signals were recorded and observed using a digital oscilloscope (Picoscope 4424™). The set-up of our experiment is shown in figure 2.

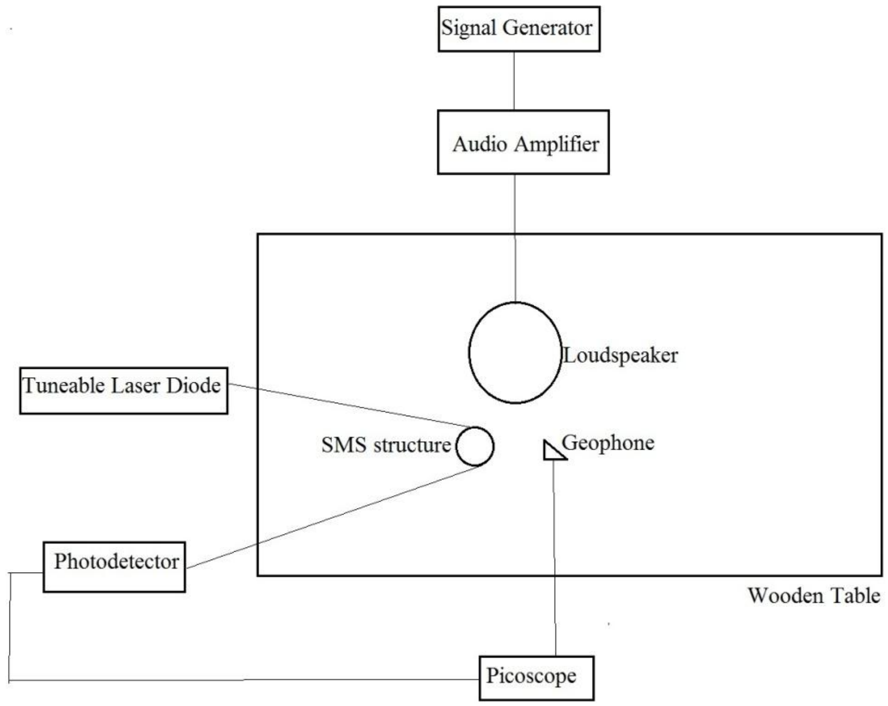


Figure 2. Experimental set-up.

3. Results and discussion

Before using the loudspeaker to excite a forced, linear, and periodic vibration to the wooden table, we conducted an impulse test by tapping slightly the table surface using a rubber hammer. Figure 3 shows the generated vibration sensed by our SMS vibration sensor (top trace, 20 mV/div) and by the GS-32CT geophone (bottom trace, 80 mV/div). It can be seen that the output of our SMS vibration sensor resembled that of the geophone.

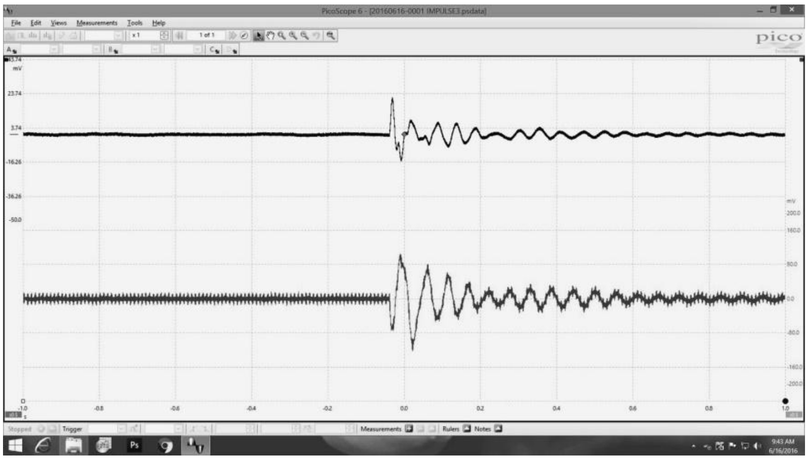


Figure 3. A typical result of the impulse test.

Figure 4 shows the recorded table vibration when we drove the loudspeaker with a 70 Hz sinusoidal signal using the signal generator. It can be seen in this time domain graph that our SMS vibration sensor (top trace, 20 mV/div) well reproduced the driving signal. From the vibration signal reproduced by the geophone (bottom trace, 40 mV/div) we can calculate the displacement of the wooden table caused by this vibration. The sensitivity of the geophone was 0.275 V/cm/s [9], it means that rms vibration velocity of 1 cm/s will produce 275 mV rms signal. The measured rms voltage at this 70 Hz vibration was 14.97 mV so the velocity was (14.97 mV)/(275 mV/cm/s) = 0.054 cm/s or 0.54 mm/s. To convert this velocity (V) value to displacement (X) we used a conversion equation $X = V/(2\pi f)$, valid for a sinusoidal vibration with frequency f [10], so that we obtain the rms displacement at this frequency is 0.0012 mm or 1.2 μm.

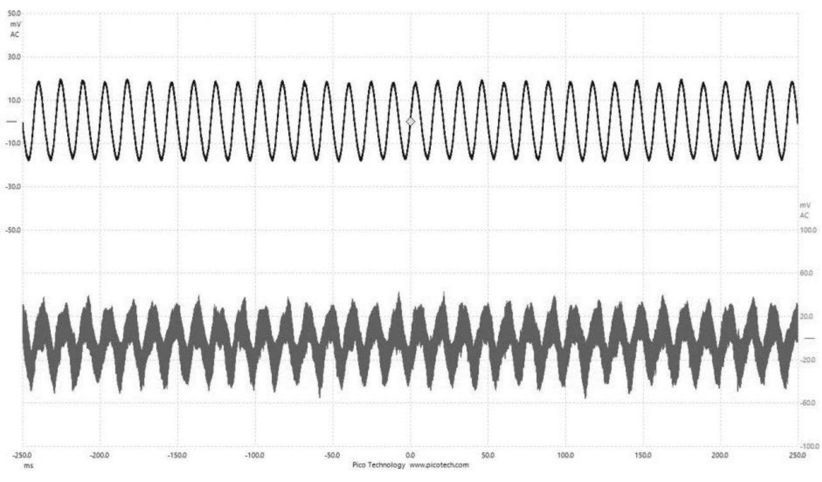
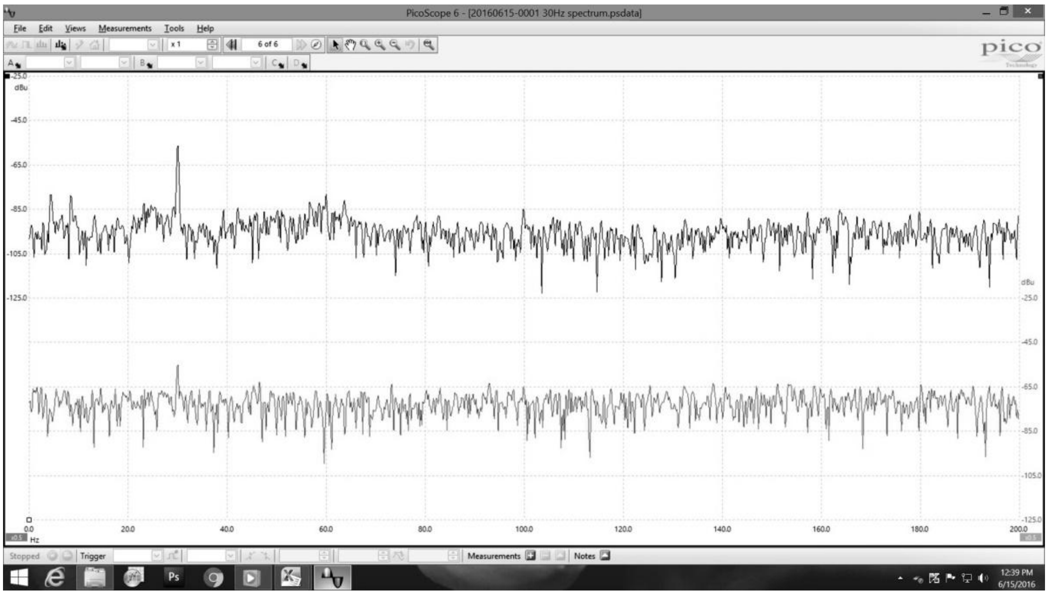
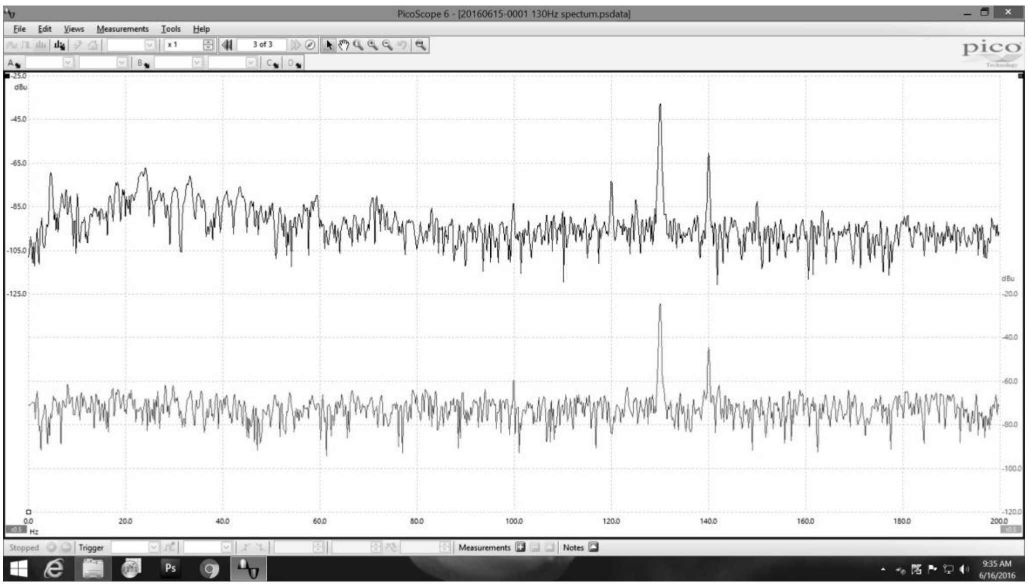


Figure 4. Recorded vibration signal at 70 Hz.

A typical result of the recorded signals from our sensors at the frequency domain is shown in figures 5(a) and 5(b) for vibrating frequency of 30 Hz and 130 Hz respectively. Again it can be seen that the signals from our SMS vibration sensor (top trace, 20 dB/div) resembled that of the geophone (bottom trace, 20 dB/div). Finally, to know the frequency response of our sensor, we drove the loudspeaker with a white noise from the signal generator. The Picoscope™ was used to record the output signal from our sensor in frequency domain when the white noise generator was turned off and then on. The output signal was saved as a CSV file and then, by using MS EXCEL™, we plotted the signal. Figure 6 shows the frequency response in 0 – 200 Hz band when there was no vibration (lower trace) and when the signal generator was turned on (upper trace). It can be seen from this plot that our SMS sensor was potential to be used in a vibration sensing system with a measurement range from 30 to 180 Hz.



(a)



(b)

Figure 5. Typical frequency domain vibration signal at (a) 30 Hz and (b) 130 Hz.

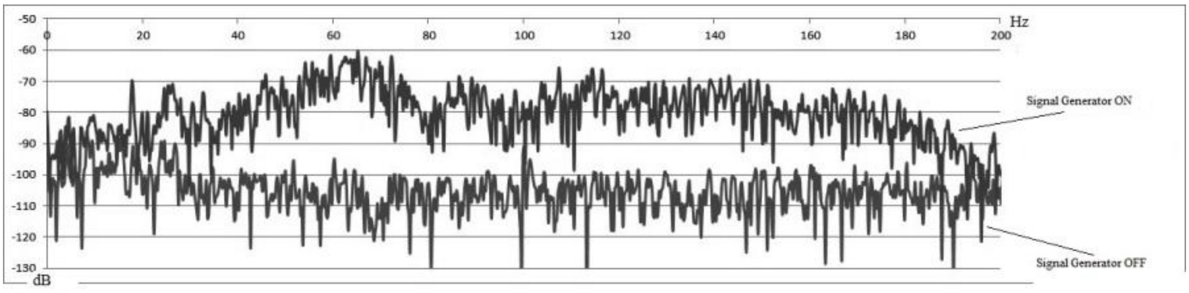


Figure 6. Frequency response of the SMS vibration sensor.

4. Conclusion

We have constructed an SMS fiber structure by splicing a section of 50/125 step index MMF between two 9/125 SMFs. To use this structure as a vibration sensor we coiled the MMF on an 80 mm diameter mini compact disc and coated the whole assembly with a TFE tape. The total weight of the sensing part was less than 10 grams so there was no loading effect when we place the sensor on most vibrating surfaces. Using a 1560 nm narrow line-width laser diode as the light source, we showed that the output of the sensor resembled that of the geophone, was able to detect 1.2 μm rms displacement, and had a good frequency response in 30 – 180 Hz band. This SMS sensor was potential for monitoring vibration in an RF-noisy condition, spark-prone environment, and remote location from the monitoring station due to the inherent optical fiber sensor advantages.

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