Hermetic All-Fiber Phase Modulators Using Joule Heating in Carbon-Coated Fibers

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Abstract: Certain applications of fiber sensors (e.g. avionics, oil industry) imply extreme operating conditions spurring the development of hermetic all-fiber devices. We present a hermetic all-fiber phase modulator based on Joule heating in a carbon-coated fiber.

OCIS codes: (290.5870) Scattering, Rayleigh; (310.3915) Metallic, opaque, and absorbing coatings; (120.4825) Optical time domain reflectometry.

1. Introduction

Optical fiber hermetic coatings play an important role in a great diversity of fiber systems, but they can be fundamental regarding fiber optic sensing systems. Many of the usual environments of fiber-optic sensors turn out to be extremely harsh, particularly in industries such as oil and gas extraction and transport [1], or even non-invasive surgery [2]. Hermetic coatings are in these cases indispensable, since they offer complete impermeability to water and hydrogen. A thin but hermetic barrier is able to protect the fiber against the diffusion of small molecules into the glass, which would otherwise derive in optical loss and strength reduction due to fatigue [3]. For these reasons, whenever a fiber system is required to operate in harsh environments where wide ranges of temperature and humidity are common, a hermetic coating is considered. This has implications for all the elements comprised in such a fiber optics system, highlighting the relevance of making hermetic-coated all-fiber devices available.

Among all the available materials, carbon represents one of the most reliable choices when a hermetic fiber coating is required. Some of the most demanding scenarios for sensing applications, for example the avionics industry, cannot indeed afford employing alternatives such as metallic coatings, which can also be applied during the fiber-draw process (allowing for long fiber runs to be manufactured). A metallic coating would imply much more weight and a poorer miniaturization of the system, due to the optical loss that small bending radii would cause in those fibers. In addition, electrical conductivity is an interesting property for a fiber coating in the field of sensing, and it has been useful to devise chemical sensors [4], or wind speed sensors [6], while it has also a central role in our study.

In this work, we take advantage of the electrical conductivity of a protective carbon coating to propose an electro-thermally controlled all-fiber phase modulator. Thanks to a small current applied on the carbon coating of a section of the optical fiber, it is possible to modify the refractive index (*n*) of its core in a controlled manner due to the temperature increase caused by Joule effect. To test the dynamic response and reliability of this effect, a sample fiber section was electrically heated while a chirped-pulse phase-sensitive optical time-domain reflectometry (CP-ΦOTDR) interrogator provided high repetition rate measurements of the refractive index variations at its core. This monitoring scheme has already proven high-sensitivity and dynamic (acoustic) performance in strain and temperature measurements [6], which makes it a suitable instrument for the characterization here proposed. The experimental results are also corroborated by a numerical model.

2. Experimental principles and setup

The sample single mode fiber (125 μm diameter) analyzed in this work was coated with a 20 nm-thick carbon layer during its drawing process. Depending on the fiber manufacturing conditions, this coating usually renders an electrical resistance which goes from 6.3 kΩ/cm to 3.7 kΩ/cm in the best observed scenario. The whole structure was also protected with a standard external acrylate coating with a thickness of around ~63 μm.

For the tests here discussed, the external coating was removed at two points (separated 3 m), allowing to place electrical contacts on the carbon coating (Fig. 1). A resistance of 1.4 MΩ was measured for the contacted 3 m fiber section (~4.7 kΩ/cm). To induce the thermal excitation of the fiber (to be monitored at its core), an electrical current was applied to the carbon layer along this section. The resulting temperature increase can be easily measured with standard infrared thermography techniques (see Fig. 1) if a heating power density of a few watts-per-meter is applied. However, a more refined technique is required to quantify the heating produced for a smaller power and, the most important, to track and quantify the refractive index dynamics induced for an alternating

Fig. 1: Thermal infrared image of the sample optical fiber segment employed in the tests and the electrical contacts performed on the carbon coating to inject the electrical current. Around 3W/m were being dissipated when the image was taken.

heating signal, which is the target of the present work. To test this regime a 50 Hz AC signal was applied intermittently at a 0.1 Hz frequency. This produced a cyclic cooling-heating response for a set of different dissipated power densities (all of them below ~12 mW/m). This mode of operation was tested to make sure the power injected did not affect the quality of the carbon layer. Its resistivity was not altered after more than 10 hours exposed to ~800 mW/m heating cycles, demonstrating the reliability of the proposed phase modulator. The fiber was placed on the top of an optical table, being surrounded mainly by *room-temperature* air. Thus, if we consider that all the power is being convectively dissipated and assume a steady state has been reached, the temperature difference with the non-excited state (T_o) would be given by the equation [7]:

$$P = h\, S\, (T - T_\mathrm{o}), \tag{1}$$

where P is the power being dissipated by the body, S is the area of its external surface, and the factor h accounts for the efficiency of the convective process. This parameter usually ranges from 2 to 25 W/(m^2 K) for free convection in gases [7]. This model has previously been able to describe the thermal behavior of a copper-coated fiber under conditions similar to the ones here considered [5]. Equation (1) is the result of the *Newton's law of cooling*, which leads to an exponential temperature evolution in time with amplitude A:

$$T(t) - T_\mathrm{o} = A\, e^{-t/\tau}. \tag{2}$$

In this model, the time constant τ is determined by the heat capacity of the fiber, its external area, and the convective efficiency (which depends on the media outside the fiber, and its flowing speed). A rough estimation of the temperature range to be expected for a certain value of P can be done considering Eq. 1. Assuming a value of h~15 W/(m^2 K), a power of a few milliwatts would be required to heat up the fiber several hundreds of millikelvins. Temperature variations in this range are enough to be dynamically monitored by means of a CP-ΦOTDR system, introduced in the following paragraphs.

In a CP-ΦOTDR setup, the instantaneous frequency of the probing pulse varies linearly (a linearly *chirped* pulse) [6]. The consecutive Rayleigh *echoes* resulting from these pulses exhibit a local time shift which is proportional to the variation of the stimulus applied to the fiber. Hence, by computing the local delay δt(z) along the trace with respect to a previous one (reference), this stimulus (temperature $\delta T(z)$ or strain $\varepsilon(z)$) can be quantified with every shot. In addition, the performance of this sensor makes easy reaching temperature/strain resolutions in the order of mK/nε. As with conventional ΦOTDR setups, the interrogator update rate is solely limited by the time of flight of the pulse, i.e., by the length of the fiber under test (typically kHz for tens of km long fibers). This makes the CP-ΦOTDR suitable for distributed dynamic refractive index variations measurements where high sensitivity is also needed. The relation between local relative refractive index change ($\Delta n(z)/n$) and the consequent observed time shift can be deduced from these principles, resulting in the following expression [6]:

$$\delta t(z) = \frac{\nu_\mathrm{o}}{\delta\nu}\, \tau_\mathrm{p}\, \frac{\Delta n(z)}{n}. \tag{3}$$

Here, τ_p represents the duration of the pulses and ν_o and $\delta\nu$ are their central frequency and sweep range, respectively. The thermo-optic coefficient [8],

$$\frac{\Delta n(z)/n}{\Delta T} = 6.92\cdot 10^{-6}\,\mathrm{K}^{-1}, \tag{4}$$

can be applied to obtain the temperature variation (instead of the refractive index change) in terms of the trace delay.

The setup of the employed temperature sensor, in comparison with a conventional ΦOTDR interrogator, requires the additional means to induce the pulse chirp and to perform the traces acquisition at its corresponding bandwidth. The chirp can be easily applied by periodically modulating the bias current of the continuous wave laser source (1550 nm), which is synchronously pulsated before entering the fiber under test (FUT). The 30 ns long pulses generated determine the 3 m spatial resolution of the sensor, which matches the length of the excited fiber region. The power returning from the FUT is conditioned and redirected to a 1 GHz fast p-i-n photodetector. Traces are digitized in a 40 GSa/s oscilloscope (providing a relative refractive index change resolution around 10^{-8} for the applied chirp) and processed in real time by a computer, which produces refractive index/temperature readouts at a 25 Hz rate.

3. Numerical and experimental results

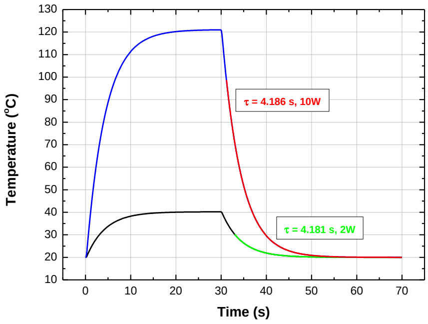

Fig. 2: FEM simulation results considering the geometry, composition and experimental setup of the sample fiber segment under natural convection, h = 25 W/(m2 K).

A simulation of the experimental conditions was performed by means of finite element method (FEM) software. For this, a convective efficiency $h = 25$ W/(m^2 K) was set. Considering a heating and cooling process, the dynamic parameter of the system, which is independent of the applied power, was estimated (Fig. 2) by fitting the temperature evolution to the exponential expression in Eq. 2. This is the behavior expected for the experimental tests. The value obtained for the time constant was $\tau^{\text{sim}} = 4.18$ s.

In Fig. 3(a) the results from the CP-ΦOTDR interrogator are plotted. We can observe that the actual refractive index oscillations typically tracked during the heating cycles exhibit a repeating exponential pattern. This behaviour corresponds to the smallest heating power density employed in the tests (4 mW/m). The data obtained for each given dissipated power value was analyzed in time but also in the frequency-domain, allowing to perform a high-pass filtering of the signal in order to discard slow room temperature or laser frequency drifts. The amplitude of the variations was also measured in the frequency-domain, providing an average of all the cycles registered corresponding to a same dissipated power value. These amplitudes are represented in terms of refractive index change in correlation with the power applied to the FUT in Fig. 3(b). The shown linear fit provides the characteristic sensitivity of the carbon-coated fiber sample in terms of relative refractive index units (RIU): $19.7\cdot10^{-6}$ RIU/W for a standard fiber with n ~1.46.

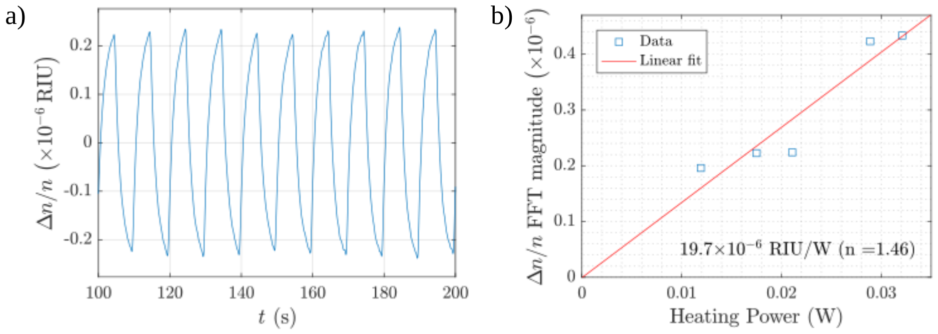

Fig. 3: a) Typical relative refractive index variation cycles induced by a 4 mW/m dissipated power; b) Cycles peak amplitude for different values of applied Joule power.

The time-domain signal was chopped in order to average all the cycles obtained for each dissipated power. An example is shown in Fig. 4, corresponding to a power density of 4 mW/m. An exponential fitting was performed over the resulting averaged curves in order to obtain the characteristic time parameter τ for the coated fiber. The average and standard deviation of the values obtained for the system was $\langle\tau^{\exp}\rangle = (1.7 \pm 0.1)$ s. This final result shows good agreement with the FEM simulations in order of magnitude of τ. However, we must remark the variability implicit in the model, as some theoretical parameters, such as the convective efficiency *h*, are not easy to estimate or control in the experimental setup.

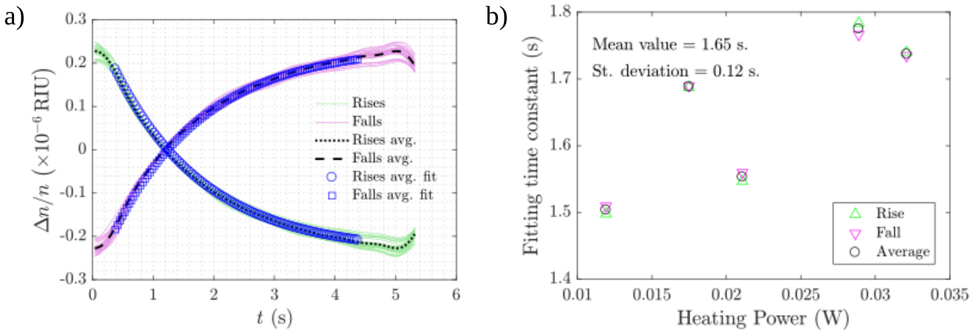

Fig. 4: a) The acquired refractive index curves are averaged to produce a representative fitting curve for each electrical power applied (4 mW/m case is shown); b) Time constant values for each power tested, as calculated from the fitting curves in (a).

4. Conclusions

In this work the viability of an all-fiber phase modulator which is based on the Joule effect to control the refractive index change in a carbon-coated fiber is shown. Owing to the thermal nature of the driving mechanism, a slow dynamics was theoretically predicted and experimentally verified, making the system suitable for applications in the frequency range of several hertzs. However, the slow time response demonstrated could be improved by embedding the fiber in a more dissipative medium, aiming to reduce its effective heat capacity and enhancing the efficiency of the heat transport mechanisms involved. On the other hand, this approach will also imply an inherent reduction of the refractive index change attainable for a same dissipated power, establishing a trade-off between refractive index modulation amplitude and fast dynamic response. The authors are currently working on several possible strategies to increase the modulation bandwidth, provided the electrical power is enough to produce the desired modulation amplitude.

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