Effect of Applying Strain to the Acousto-Optic Transducer All Optic Fiber Transmittance Function in the Audible Frequency Range

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Abstract: - This paper reports the effect of applying strain to the birefringent optical fiber segment in an all fiber acousto-optic transducer. Such transducer is based on a Sagnac interferometer. The system is an acousto-optic modulator (AOM), used for sensing acoustic signals in the audible frequency range. The AOM uses an optical source (laser) at 1550 nm.

Key-Words: - Transducer, acousto-optic, voice, transmittance, audible, interferometer, Sagnac, optic fiber, strain function.

1 Introduction
Among the applications of the acousto-optic phenomenon, it is sensing acoustic signals in the audible frequency range. Different techniques and experimental methods regarding this kind of applications have been reported, in recent years[1-3]. This paper presents an experimental arrangement for sensing acoustic signals in the audible frequency range. It uses a Sagnac interferometer all optical fiber and as core element, a high birefringence fiber segment which acts as a primary transducer, that is, the acoustic signal interacts with the fiber segment, placed inside an acoustic resonator [4]. This is where the birefringent fiber undergoes gradually to mechanical stress. The mechanical signal tone (incident acoustic signal) modifies the resting state of the high birefringence fiber tied to the acoustic resonator, and induces a vibration in the fiber as a function of the signal to be sensed (incident), modifying the fiber physical parameters. The refractive index of the fiber is modified depending on the frequency of the acoustic signal to be sensed, generating the modulation of the laser beam flowing through the fiber optic loop system [5].

It is very important to make the necessary measurements and the characterization of the AOM system. Within the data of interest is the transmittance function, which is obtained by exposing the AOM to different physical conditions.

We are particularly interested in the effect of applying strain to the birefringent fiber segment and thereby to study modifications to the transmittance function of the AOM.

2 Problem Formulation
Measurements made, using the oscilloscope regarding the shape and phase of the signal, show a phase shift between the electrical signal with amplitude $A_0$, at a frequency $f_0$, supplied by the function generator and the electrical signal registered by the photo detector which is the signal processed by the AOM. This phase shift is predicted and justified by theoretic transmittance function. The simulation of this argument is given by equation 2. The relationship between transmittance and reflectance is as follows:

$$T = 1 - R$$

Considering the fields’ intensity $|E_0|$, the coupling factor $\alpha$ of the beam splitter and the phase, it is obtained that:

$$T = \frac{|\bar{E}_0|^2}{|E|^2} = 1 - 2\alpha(1 - \alpha)\left[1 + \cos(\Phi_{L} - \Phi_{R})\right]$$

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Where the phase is given by equation 3:

\[
\Delta \Phi = (\Phi_{xy} - \Phi_{yx}) = \frac{2\pi}{\lambda} (n_x - n_y) L
\]

(3)

The last equation considers the wavelength of the optical source, the fiber length and its refractive indexes.

By varying the physical parameters of AOM regarding to the birefringent fiber length, an increment in the length of the closed loop in the Sagnac interferometer (SI) is obtained. These changes affect the transmittance predicted by equation 2. The Figure below shows this effect.

Fig.1 Normalized transmittances corresponding to a pair of Sagnac loop lengths, \(L = 32\) cm and \(L = 50\) cm

The nature of the transmittance shows consecutive maximums and minimums, this ensures a positive or negative modulation depending on the operating point of the AOM.

2.1 Transmittance Function

Sagnac interferometer is made up of a 2×2, 50/50 fiber coupler of 3 dB at 1550 nm (F-CPL-F22155-Newport), a segment of high birefringence fiber of length \(L\) (F-SPPC-Newport). The segment \(L\) of the fiber, into a resonance box, is strained by its extremes using a 61 grams weight, as it is shown in Fig. 2.

Fig.2 Schematic diagram of the detection system for the acoustic signal

Input power \(P_{in}(\lambda)\) is generated by a pigtail ILD stabilized with a fiber grating Bragg (ILD-ETEK-1550), and \(P_{out}(\lambda)\) is the output power of the Sagnac Interferometer. This SI is adjusted [10-12]. The SI transmittance function in terms of power is shown in Equation (4), [10, 11]:

\[
T_{SI} = \frac{P_{out}(\lambda)}{P_{in}(\lambda)} = 1 - 2\alpha(1-\alpha)\left[1 + \cos(\Delta \phi_{a})\right],
\]

(4)

Where \(\alpha\) is the coupling coefficient of the 2×2 fiber coupler, \(\Delta \phi_{a} = (2\pi/\lambda) \Delta n_{a} L_{v}\), \(\Delta n_{a} = n_{ax} - n_{ay}\), and \(n_{ax}, n_{ay}\) are the corresponding refractive-index for each birefringent fiber axis. Sub-index \(a\) indicates that the variable is evaluated at 21°C.

It is necessary to know the fiber birefringence value, before to construct a SI. Thus, Equation (5) relates the next variables: \(\lambda, \Delta n_{a}, L,\) at 21°C, and without mechanical stress \((\Delta n_{a} = \Delta n_{ao})\):

\[
\Delta n_{a} = \frac{\lambda^{2}}{\Delta \lambda^{2}} \frac{1}{L}.
\]

(5)

2.2 Acousto-optic modulator transmittance model

With the previous arguments, it is ensured that the system’s transmittance function accepts shifting to the right or left to change the physical parameters of the interferometer. This opens the possibility of positive or negative modulation.

In order to obtain the transmittance function depending on the transversal vibration modes induced in the segment, \(L_{v}\), of the birefringent fiber of length \(L\) in the Sagnac Interferometer, the phase
changes, $\Delta \phi$, produced through the loop segments, $L-L_v$ and $L_v$ must be considered, to align the orthogonal components $x$ and $y$ of the cross section of birefringent fiber, which propagate across of the Sagnac loop, as shown in Fig. 3.

Based on the experimental results, the velocity of change in the refraction index of the birefringent fiber in each axis with regard to the induced vibration, $i_m(t)$, is predominantly linear, as it is expressed in Equations (6) and (7):

$$\begin{align*}
n_{ix} &= n_{x_0} + \frac{\partial n_x}{\partial i_m} \cdot i_m, \\
n_{iy} &= n_{y_0} + \frac{\partial n_y}{\partial i_m} \cdot i_m.
\end{align*}$$

Where $n_{x_0}$, $n_{y_0}$ are the refraction indexes $x$ and $y$ in absence of vibration, and $n_{x_v}$, $n_{y_v}$ are the induced refraction indexes in each of the axis of the birefringent fiber, which depend on $i_m(t)$. It must be emphasized that this analysis is performed at a constant temperature of laboratory.

Thus, given that $\Delta n_i = n_{ix} - n_{iy}$,

$$\Delta n_i = n_{x_0} - n_{y_0} + \left(\frac{\partial n_x}{\partial i_m} - \frac{\partial n_y}{\partial i_m}\right) \cdot i_m = \Delta n_{x_0} + \frac{\partial \Delta n}{\partial i_m} \cdot i_m,$$

where $\Delta n_{x_0}$ is the birefringence of the fiber in absence of vibration.

$$\frac{\partial \Delta n}{\partial i_m} = \delta_{disp},$$

$\delta_{disp}$ is the induced dispersion birefringence, it is proportional to the acousto-optic modulator gain, and represents the velocity of birefringence changes in the fiber with respect to the contained oscillation modes in $i_m(t)$. Thus, the phase difference reached by the orthogonal components, at the end of their propagation across the complete segment, $L$, is obtained in Eq. (10):

$$\Delta \phi[i_m(t)] = \phi_x - \phi_y = \frac{2\pi}{\lambda} \Delta n_{x_0} \cdot (L-L_v) + \frac{2\pi}{\lambda_0} \Delta \phi_v \cdot i_m \cdot (L_v-L),$$

The previous equation is equivalent to Equation (11):

$$\Delta \phi[i_m(t)] = \Delta \phi_v + \Delta \phi_v[i_m(t)] = \frac{2\pi}{\lambda_0} (\Delta n_{x_0} L + \delta_{disp} i_m(t)L_v),$$

(11)

The changes in phase due to $\Delta \phi[i_m(t)]$ are hardly amplified as $L_v$ increases. Equation (11) will help to optimize the modulator experimental response at the operation point, the gain and the appropriate sensibility[13-16]. $T[i_m(t)]$ of the AOM is described through Eq. (12),

$$T[i_m(t)] = \frac{1}{2} + \frac{1}{2} \cos\left(\frac{2\pi}{\lambda_0} (\Delta n_{x_0} L + \delta_{disp} i_m(t)L_v)\right).$$

(12)

The spectral shifting velocity of $T[i_m(t)]$ due to $i_m(t)$, is calculated through Eq. (13),

$$\frac{\partial \lambda}{\partial i_m} = \frac{\lambda_0 \delta_{disp}}{\Delta n_{x_0} L}.$$

(13)

The modulation capacity of the interferometer depends on the frequency of the induced vibration modes $i_m(t)$. This capacity depends proportionally on the birefringence dispersion, $\delta_{disp}$. Shifting velocity can be amplified in relationship with ($L_v/L$), causing an increment in the sensibility of the acousto-optic modulator for each vibration frequency of the birefringence fiber strained by the ends.

The Figure below shows this property of the interferometer and several working points.

This Figure shows the areas of positive and negative modulation of the AOM [6-10].

Negative modulation

For the behavior of $T(\lambda, \Delta \phi_{\text{init}}, i_m(t))$ in the region $\lambda_0 < \lambda$, its cosine profile can be approximated with the tangent linear equation at the point $P(\Delta \phi_{\text{init}}, 0.7)$, which has a negative slope $m$, this is expressed in the Eq. (14),

$$T[i_m(t)] = \frac{\partial T}{\partial \Delta \phi_v} (\Delta \phi_v - \Delta \phi_{\text{init}}) + \frac{7}{10}.$$

(14)
Where \( m_1 = (-\partial T / \partial \Delta \phi) \approx -0.47 \) is the negative slope in the middle region between the crest and the valley of the cosine function.

**Positive modulation**

For the behavior of \( T(\lambda_0, \Delta \phi_0, i_n(t)) \) in the region \( \lambda_0 < \lambda \), its cosine profile can be approximated with the tangent linear equation at the point \( P(\Delta \phi_0, 0.2) \), which a positive slope, \( m \), this is expressed in the Eq. (15),

\[
T[i_n(t)] \approx \frac{\partial T}{\partial \Delta \phi} \cdot (\Delta \phi - \Delta \phi_0) + \frac{2}{10}, \quad (15)
\]

Where \( m_2 = (+\partial T / \partial \Delta \phi) \approx +0.47 \) is the positive slope in the middle region between the crest and the valley of the cosine function. In both cases, into the linear region:

\[
0 < \Delta \phi - \Delta \phi_0 \leq 1.06 \text{ rad}, \quad (16)
\]

In consequence the laser modulation in nonlinear regions of the transmittance function \( T(\lambda_0, t) \) [16-19] must be avoided. The Phase relationship between \( i_n(t) \) and \( P_{\phi}(t) \) is \( \pi \) rad for negative modulation, and \( 0.0 \) rad for positive modulation. Whatever \( T(i_n) \) is proportional to \( i_n(t) \).

### 3 Verification of Phase Shifting

The block diagram for the experimental arrangement implemented in the laboratory is shown in the following Figure 2.

Applying strain to the birefringent fiber segment, the physical parameters in the AOM are changed. Measurements were made in the transmittance function for different strains applied, and the predicted shift above was observed. A couple of graphs were obtained and reported.

The detected signal was measured. The following two Figures show waveforms measured on the oscilloscope. They show the phase shift between the incident signal and the signal recorded by the system.
Fig. 7 Graph for the incident signal and the recorded one out of phase

Figures 6 and 7 show the measurements made in the laboratory that confirm the prediction.

4 Conclusion

The AOM physical parameters are modified in function of the interaction with the fiber. In particular, with the discrete mechanical stress, applied to the birefringent fiber segment in the interferometer loop, a shift in the transmittance function can be observed, this can be verified by the graphs experimentally obtained. The applied mechanical stress changes the refractive index of the fiber, generating this property. Finally, Figures 6 and 7 show the waveforms of the incident signal and the signal detected using the proposed system in the laboratory. The phase shift can be observed in the oscilloscope used for the experimental measurement.

In this research it has been demonstrated the possibility of using a high birefringence optical fiber interferometer Sagnac as a linear laser acousto-optic modulator for frequencies from 20 Hz to 20 kHz, at 1550 nm. The linear modulation has been performed with the intensity of a laser beam of 1550 nm at 21°C. As a resonant system, it shows a gain spectrum distributed in adjacent lobes.

References:
[12] Kentaro Nakamura et al, A two-dimensional optical fiber microphone array with matrix-


