Compact Acousto-Optic Interrogator for Fiber Optic Bragg Sensors

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Abstract—**Fiber optic sensors are widely used to control both strain and temperature by measuring the wavelengths of optical signals reflected from multiple gratings incorporated at different places of a long fiber. Traditionally the expensive tunable lasers or optical spectrum analyzers are used for wavelength interrogation. This paper proposes to replace tunable laser by a broadband optical source incorporated with novel thin linewidth acousto-optic (AO) tunable filter. It utilizes hundreds of times expanding optical beam by multiple reflection from photonic crystal rows of air holes in $LiNbO_3$ waveguide. New AO interrogator design is numerically studied for a short structure (with 32 photonic crystal rows) by two-dimensional finite difference time domain (FDTD) method. Extrapolation of these results to large structure sizes (around 1 cm) demonstrates the possibility to develop compact AO interrogators with 0.4 pm wavelength resolution and 40 nm tunable range around 1550 nm.**

Keywords-component; Fiber optic sensors; interrogator; acousto-optics; tunable filter; FDTD.

I. DESIGN OF ACOUSTO-OPTIC INTERROGATOR

The general conception of interrogation system is presented in Fig. 1. The approach is based on using AO filter both for selecting the working band of broadband light source as well as for filtering the optical signal reflected from fiber Bragg grating (FBG), which is measured by the photodetector. Either light-emitting diodes or amplified spontaneous emission (ASE) fiber sources could be used to illuminate the FBG sensors [1].

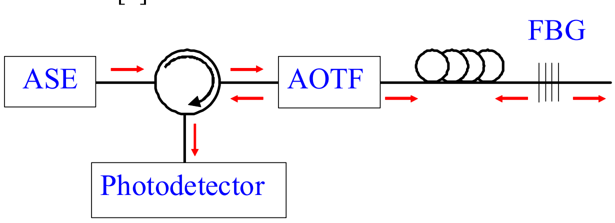

Figure 1. Schematic of acousto-optic interrogator with the circulator.

The principle of device sensing can be briefly described as follows. The circulator or 3dB coupler/splitter is used to select contra directional optical beams (from ASE and directed to photodetector). Acousto-optic tunable filter (AOTF) is swiping up and down the optical band launched in fiber by linearly changing in time the operation radio frequency (RF). Part of incoming optical energy at a particular wavelength (depending on the sensor environment) has to be effectively reflected from FBG, comes back through AOTF and is detected by the photodetector. The maximum of signal peak occurs at FBG drop wavelength. It is measured through a joint analysis of several functional dependences, i.e. photodetector signal versus time, RF frequency versus time and wavelength versus frequency. Due to time delay between launching and returning (from FBG) optical signals, they are filtered by AOTF operated at slightly different wavelengths. For error self compensation, the actual interrogator wavelength of FBG sensor is measured as an average value, determined at increasing and decreasing slopes of RF variation.

II. SIMULATION OF ACOUSTO-OPTIC INTERROGATOR

It is evident that the smaller AO filter linewidth, the better wavelength resolution of the interrogation. Currently used AO technology has a principal limitation in the filter linewidth. Multireflector (MR) filtering technology [2-4] could improve it by several times, together with a simultaneous decrease of device sizes and switching times, as well as providing an extremely high temperature stability, about 0.01 nm/C° [3]. Although MR AO devices have not yet been experimentally demonstrated, we believe that existing technology of photonic crystals [5] etched in $LiNbO_3$ crystals will make this technology reliable.

Photonic crystal rows of air holes tilted at appropriate angles have been used as power and polarization beam-splitters [6-7] and for design of AOTF [4]. Currently, we present preliminary simulations of AO interrogator (see Fig. 2) on similar structures by FDTD method in two-dimensional (2D) approximation [4]. In order to describe FBG response we use Fabry-Perot (FP) filter (see circle in the left corner of Fig. 2) constituted by two strong parallel mirrors with additional 45° partial reflector. For independent control of AO interrogation the two additional partial mirrors are used to select contra directional optical beams which are measured by power monitors (see green strips in Fig. 2). These monitors measure the power of incident beam (1), interrogated signal of back reflected beam (2), transmitted (3) and reflected signals (4) of FP filter and Drop signal (5) at AOTF output (see Fig. 5). Interrogation algorithm is based on measuring the total power (integral of signal (2) over a wide range from 1.48 µm to 1.64 µm) of back reflected beam, corresponding to different acoustical wavelengths, i.e. different filtered wavelengths, as shown in Fig. 2. By fitting the signal wavelength dependence by a Gaussian function and taking into account the linear $\lambda_f(\Lambda)$ slope, the wavelength λ_c of Fabry-Perot sensor element can be found. In the particular case of short AOTF with small aperture D = 150 µm (FWHM $\delta\lambda$ = 4.4 nm), we have got λ_c = 1566.67 nm with a standard error $\delta\lambda_s$ = 0.03 nm. It provides an error estimation vs FWHM: $\delta\lambda_s \sim 0.007\times\delta\lambda$.

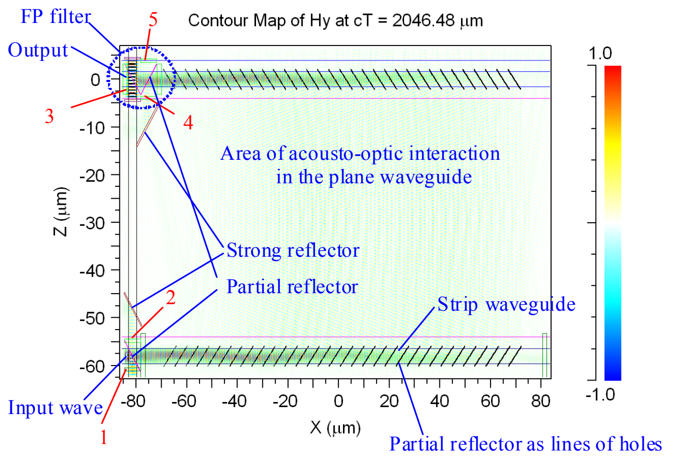

Figure 2. Wavelength interrogation by AOTF. Λ = 1.6456 µm, 32 partial reflectors with small period D = 4.4 µm (2D FDTD simulation).

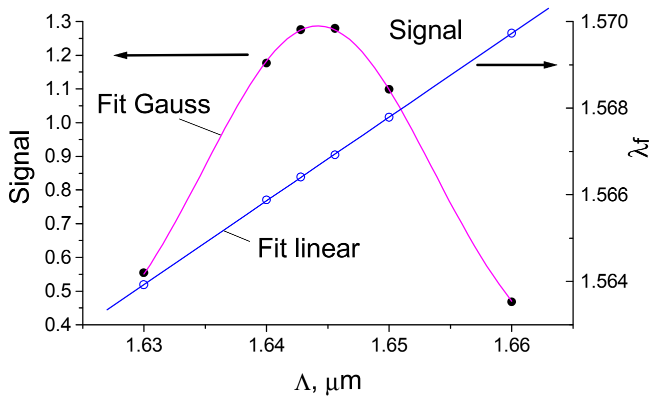

Figure 3. Wavelength interrogation by AOTF. Measured signal by photodetector and filter wavelength (λf) at different SAW wavelengths Λ (2D FDTD simulation).

Taking into account an empirical relation [4] between acoustooptic aperture L and linewidth, $\delta\lambda=0.6\times\lambda_c^{\ 2}/(2N_mL)$, our results (see Table I) can be scaled to practically used $LiNbO_3$ waveguide structures with large D, L and moderate SAW frequencies. Here N_m=2.2828 is a guided mode index, $\Delta\lambda$ is the tuning range, f_0 is the central SAW frequency.

TABLE I. PARAMETERS OF AO INTERROGATOR

D (µm)	$\delta\lambda$ (nm)	$\Delta\lambda$ (µm)	f_0 (MHz)	$\delta\lambda_s$ (pm)	L (mm)	Remark
4.4	4.4	110	2125	30	0.14	FDTD
4.4	4.5	120	1989	31	0.14	Estimate
13	1.5	40	673	11	0.42	Estimate
13	0.06	40	673	0.4	10.0	Estimate

III. CONCLUSIONS

The new design of a compact FBG interrogator based on acousto-optic filter using row of air holes in multi reflector beam expanders is proposed and examined by 2D FDTD using a commercial software tool. Results prove that this novel AO interrogator could provide the wavelength resolution up to 0.4 pm. It utilizes broad band optical source and does not need any expensive tunable laser or optical spectrum analyzer. It can be used as interrogator component for remote control of multi-channel fiber Bragg gratings or integrated optics sensors based on wavelength interrogation (depending on environmental conditions). This novel interrogator has smaller sizes and much cheaper than its counterparts, then very good for multiple practical applications.

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