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Acousto-Optic Amplitude Modulator based on a Long-Period Fiber Grating Mach-Zehnder Interferometer

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The success of fiber optics can be attributed largely to the efficient replacement of bulk optical components with equivalent fully integrated in-line fiber devices. The fiber grating is an excellent example of an all-fiber component that has become essential to the development of new optical fiber systems and has found a variety of applications in telecommunications and sensing. In particular, a fiber Mach-Zehnder interferometer based on a pair of long period fiber gratings (LPG) was proposed for measuring UV-induced refractive index changes in fibers and the refractive index of the surrounding medium [1]. Optical phase modulation at frequencies up to 800 MHz has been demonstrated using a piezoelectric zinc oxide (ZnO) film sandwiched between two metal electrodes, coated on the surface of an optical fiber [2]. Recently, an all-fiber modulator that combines a fiber Bragg grating with a ZnO transducer was investigated [3]. The straining action of the piezoelectric coating changes the grating period and the refractive index, thus achieving the modulation of the Bragg grating resonance wavelength. Here, we report on an all-fiber acousto-optic modulator that combines a long period fiber grating Mach-Zehnder interferometer with a ZnO thin-film transducer. The ZnO layer is coated onto the optical fiber in between the gratings. The strain-induced changes in the refractive index of the fiber core and cladding allow for the modulation of the phase difference between the two arms of the interferometer. Hence, amplitude modulation at high frequency can be performed at the LPGs resonance wavelengths.

A long period fiber grating consists in a periodic variation of the core refractive index along the fiber. The operation of a LPG is based on the coupling between the fundamental core mode HE_{11} and the cladding modes HE_{1m} (m = 2, 3, ...). The coupling wavelength λ_{1m} for the cladding mode HE_{1m} is defined by the phase matching condition $\lambda_{1m} = (n_{11}^{eff} - n_{1m}^{eff})\Lambda$, where Λ is the grating period and n_{11}^{eff} and n_{1m}^{eff} are the effective refractive indices of the fundamental and cladding modes, respectively [4]. A pair of LPGs can operate as an all-fiber Mach-Zehnder interferometer [1]. The configuration of the device is depicted in Fig.1. Each grating acts as a wavelength-dependent beam splitter. LPG1 couples a part of the incident core mode into the co-propagating cladding mode. The two modes propagate independently until they reach LPG2, where they interfere. Sinusoidal interference fringes then appear in each stop-band of the long period grating transmission spectrum. The output core intensity is a sinusoidal function of the phase difference, $\Delta\varphi$, between the two interferometer arms [1,5]:

$$\Delta\varphi = \frac{2\pi}{\lambda}(n_{11}^{eff} - n_{1m}^{eff})L = \frac{2\pi}{\lambda}\Delta n_{1m}^{eff} L, \qquad (1)$$

where λ is the wavelength in vacuum, L is the distance between the two LPGs and Δn_{1m}^{eff} is the core-cladding refractive index difference for the coupling to the HE_{1m} cladding mode. Modulating the phase difference between the interferometer arms allows for the modulation of the fringe pattern and thus of the transmitted intensity at the wavelength λ. From Eq. (1) it follows that the change in phase difference between the two interferometer arms $d(\Delta\varphi)$ is inversely proportional to the wavelength λ and increases with the distance L between the two gratings:

$$d(\Delta\varphi) = \frac{2\pi}{\lambda}\left[L\, d\left(\Delta n_{1m}^{eff}\right) + \Delta n_{1m}^{eff}\, dL\right] \tag{2}$$

Efficient modulation can be realized by coating the fiber section between the LPGs with a cylindrically symmetric piezoelectric transducer. The coated fiber acts as a cylindrical acoustic resonator and standing acoustic waves interact with the optical field in the core and cladding region [6]. The strain-induced effective index change $d\left(\Delta n_{1m}^{eff}\right)$ is thus given by the overlap integral between the radial intensity distributions of the core and cladding modes and the strain field of the acoustic wave.

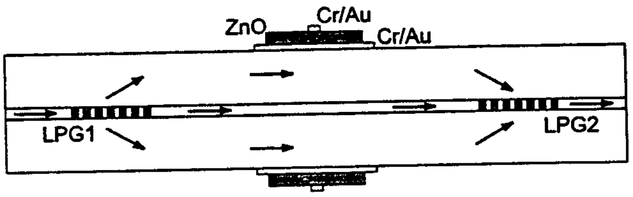

Fig. 1: Acousto-optic LPG Mach-Zehnder modulator

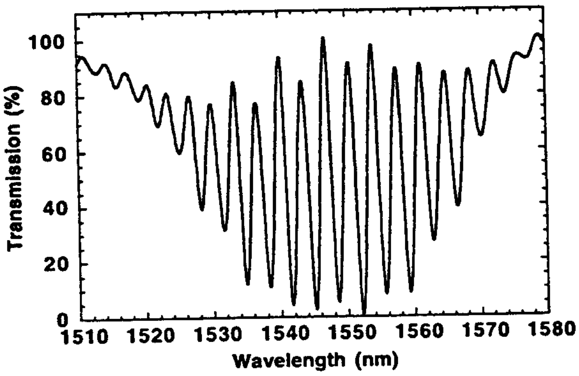

Fig. 2: Transmission spectrum of the LPG Mach-Zehnder configuration

Two LPGs were fabricated in a step-index germanosilicate fiber with a GeO_2 concentration of 12 mol.% in the fiber core using frequency doubled CW Ar^+ laser light at the wavelength of 244 nm. The fiber has core and cladding diameters of 3.5 and 125 μm, respectively. The step-by-step technique was used to obtain the periodic modulation of the refractive index in the fiber core. The two gratings have a period of 160 μm and a length of 6 mm. The distance L is 58 mm. The transmission spectrum of the grating interferometer, shown in Fig.2, was recorded with a tunable external cavity semiconductor laser, a photodetector, and a digital oscilloscope. A spectral resolution of 50 pm was used. The cladding mode coupled by the gratings is the $HE_{1,10}$. After laser irradiation, the fiber section including the long period gratings was cut to 19 cm length and any remaining polymer coating was stripped off. The following layers were deposited onto the fiber section between the LPGs as shown by Fig.1: i) a Cr/Au inner electrode with a thickness between 150 and 250 nm by thermal evaporation; ii) a ZnO piezoelectric jacket of about 11 μm thickness by reactive dc magnetron sputtering; iii) a Cr/Au outer electrode with a thickness between 270 and 330 nm by thermal evaporation. Bottom electrode, ZnO coating, and top electrode have lengths of 7, 3, and 0.5 mm. The coating process reduced the fringe visibility of the transmission spectrum to about 50 %. This is due to the power loss at the bottom electrode and can be minimized decreasing the length of the transducer coatings. Electrical pressure contacts to the fiber device inner and outer electrode were made using 30 μm diameter gold wires, that were fixed with silver paint to a SMA standard connector. Modulation of the output intensity was measured with the tunable laser, a fast photodiode and a network analyzer. The wavelength of the tunable laser was placed at the 3-dB point of an interference fringe and the modulation of the transmitted intensity was recorded. The wavelength modulation amplitude was then determined from the slope of the transmission spectrum at the laser wavelength. Figure 3 shows the wavelength modulation amplitude as a function of frequency between 10 MHz and 1.2 GHz for an applied power of 10 dBm. This corresponds to source voltage amplitude of 2 V.

The frequency response of the transducer is broad-band with superimposed resonance peaks spaced by about 45 MHz due to the fiber-coating resonator structure [2].

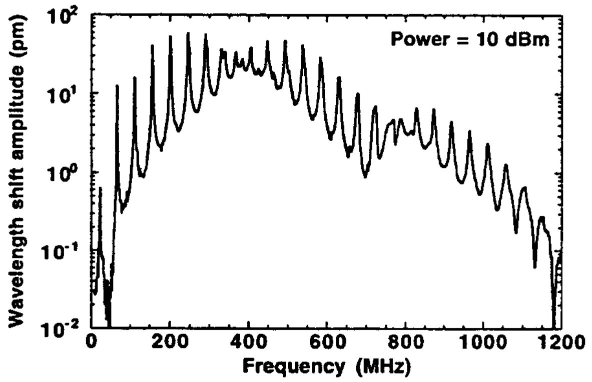

Fig 3: Frequency response of the amplitude modulator

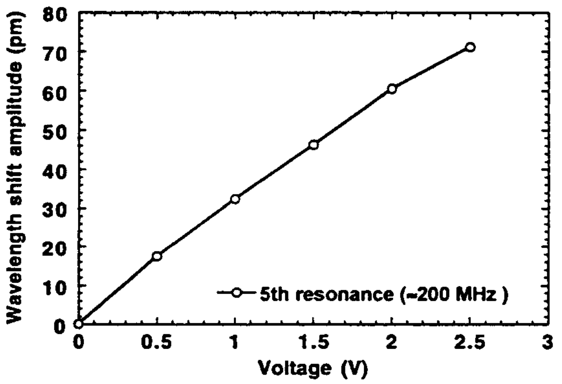

Fig 4: Voltage response of the modulator

Figure 4 shows the wavelength modulation amplitude as a function of the source voltage at the 5th resonance (≈200 MHz). A linear dependence of the wavelength modulation amplitude is observed for relatively low voltages as for ZnO phase modulators [2]. At higher voltages the response shows a non-linearity and a shift of the resonant frequency to a higher value. A maximum modulation of 90 pm and an efficiency of 28.5 pm/V were measured. The modulation depth can be improved by increasing the distance between the two LPGs and reducing the absorption caused by the inner electrode of the transducer.

An all-fiber amplitude acousto-optic modulator based on a LPG Mach-Zehnder and a ZnO transducer was realized for the first time. Modulation of the LPG Mach Zehnder spectrum was observed in the frequency range from 10 MHz to 1.2 GHz with a maximum value of 90 pm. Wavelength modulation could be performed at any desired wavelength by fabricating two LPGs with the right period. This component shows a great deal of promise for active-mode locking and external amplitude modulation of fiber lasers.

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