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INTEGRATED OPTICAL HETERODYNE INTERFEROMETER IN LITHIUM NIOBATE

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A high performance integrated acousto-optical heterodyne interferometer has been developed for vibration measurement. All components including an acousto-optical TE–TM mode converters, two electro-optical TE–TM converters, two polarization splitters and two phase shifters are integrated on a X-cut Lithium Niobate substrate. The fully packaged optical integrated circuit (optical-IC) coupling with three fibers optics pigtails gave a signal-to-noise ratio of 69 dB with at 3 kHz bandwidth by using a commercial DFB laser diode as a light source with 1561 nm emission wavelength and a PIN-FET balanced receiver.

Keywords: Optical-IC, acousto-optic, electro-optic, vibrometer.

1. Introduction

Integrated optical heterodyne interferometers for applications such as Doppler-velocimetry, frequency analysis of vibrating surfaces and contact-free distance measurements promise high sensitivity, rugged construction, small overall size and possibly low fabrication costs. Different versions of interferometers have recently been developed in glass,[1,2] on silicon,[3,4] with polymer waveguides and in $LiNbO_3$; the first optical systems with integrated optical interferometric sensor on silicon and in glass are now commercially available.

Contrary to glass, silicon and polymers, $LiNbO_3$ allows to take advantage of its excellent electro-optical and acousto-optical properties; both can be exploited to develop heterodyne interferometers of ultimate sensitivity using integrated frequency shifters, beam splitters and polarizing optics.

Electro-optical interferometers in $LiNbO_3$ for displacement and velocity measurements have been pioneered by Nishihara and co-workers.[5] They developed

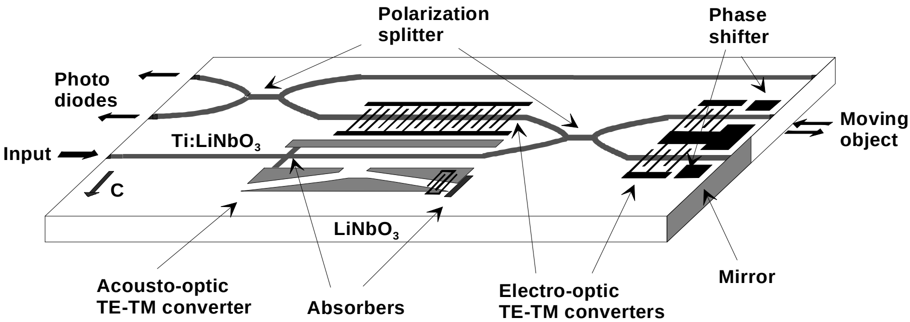

Fig. 1. Scheme of the integrated optical heterodyne interferometer.

a series of integrated Michelson-interferometers of impressive performance using serrodyne phase modulation to generate a frequency-shifted wave required for heterodyne detection. The same method was applied by Suchoski *et al.*,[6] who developed a heterodyne interferometer for vibration analysis.

A first version of an acousto-optical heterodyne interferometer has been fabricated and thoroughly studied by F. Tian *et al.*[7] It consists of acousto- and electro-optical components, polarization splitters, and mirrors. The input and output waveguides have been connected with single mode fibers. Recently, we have presented the integrated acousto-optical heterodyne interferometer which operated with a Ti:Er:$LiNbO_3$ DBR-Waveguide Laser. It allows to measure moving and vibrating object with 65 dB signal-to-noise ratio at 3 kHz bandwidth.[8]

In this contribution we present and discuss the new integrated acousto-optical heterodyne interferometer in X-cut, Y-propagating (see Fig. 1). By using an external DFB laser diode as a light source with 1561 nm emission wavelength the fully packaged interferometer gave a signal-to-noise ratio of 69 dB with balanced detection at 3 kHz bandwidth. We describe the current developments towards more complex structures including a waveguide Ti:Er:$LiNbO_3$ DBR Laser at the input (see Fig. 5).

2. Integrated Waveguide Devices

To fabricate the interferometer optical circuit a $LiNbO_3$ substrate of X-cut orientation (Y-propagation) is used. Acoustical and optical waveguides are fabricated by Ti-indiffusion technology. In a first step the acoustical waveguides are defined by an indiffusion (31 h at 1060°C) of a Ti-layer of 160 nm thickness into the cladding region of the acoustical guiding structures, which are 19.1 mm long tapered acoustical directional couplers.[9]

Subsequently, the optical waveguide structure is fabricated again by Ti-indiffusion (9 h at 1030°C). For single mode waveguides Ti stripes of 100 nm thickness and 7 μm width are indiffused. The optical waveguides form a Michelson interferometer consisting of a reference arm, a measuring arm and the additional polarization splitter with two waveguide outputs. The internal losses of the optical waveguides are ~ 0.06 dB/cm and ~ 0.2 dB/cm for TM- and TE-modes, respectively.

A specially designed directional coupler with a double mode central section of length 320 μm and width of 14 μm is used as polarization splitter.[10] The full angle between the coupler arms is 0.62°. The splitting ratio is then defined as the quotient of the optical power in the "wrong" output and the sum of the powers in both output ports. The splitting ratios have been determined to be better than -20 dB for both polarizations.

In the next fabrication step interdigital transducer electrodes consisting of 24 finger pairs to excite surface acoustic waves (SAW), electro-optic converter electrodes consisting of 324 pairs with 21.6 μm periodicity and phase modulator electrodes of 4 mm length are simultaneously deposited. The definition of the electrode structures is also done by photolithography. However, in contrast to the definition of the waveguides, here a lift-off process for an aluminum layer is used. To avoid extensive losses of the optical wave an aluminum oxide buffer layer of 300 nm height is placed between the substrate and the electrodes.

For applications of the interferometer it is necessary to provide the device with fibers and connectors. Three fibers pigtails are coupled to the chip, one for the input and two for the output. To obtain a larger glueing-surface and thus higher mechanical stability the fiber is fixed into the groove of a silicon block. The endfaces of the waveguide chip are properly polished and provided with an anti-reflection coating (ARC) to keep reflections to a minimum. An ARC for the air/glass-interface is fabricated using one layer each of SiO_2 and Y_2O_3.

3. Operation of the Interferometer

Characterization of the interferometer has been done by using a 1561 nm a commercially DFB laser diode, with an isolator between laser and interferometer. The laser has a narrow linewidth of 0.8 MHz. TM-polarized light of frequency f_o is fed into the integrated optical heterodyne interferometer chip (see Fig. 2). It first passes the acousto-optical TE–TM mode converter; half of the optical power is converted into TE polarization. The frequency of the generated TE-mode is shifted by the acoustic frequency f_a (≈ 170 MHz).

Both, TE- and TM-polarized waves are separated by the subsequent passive polarization splitter and fed into the reference and measuring arms of the (Michelson) interferometer. In both arms the electro-optic TE–TM mode converters and phase shifters are used to rotate the polarizations of the back-reflected waves by 90° without an additional frequency shift. The result is that both waves are recombined by the polarization splitter and fed into the output arm without any principle loss and without feedback to the optical source. The reference arm is terminated by a metallic end face mirror. The measuring arm is extended via an external collimating optics which focuses the outgoing light and collects the back-reflected, phase-/frequency modulated light from the moving object to be measured.

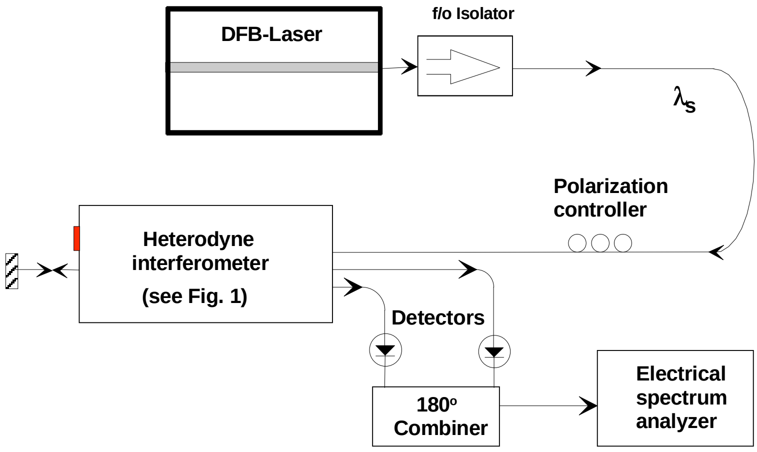

Fig. 2. Set up to characterize the heterodyne interferometer using a DFB Laser diode.

In the output waveguide, the polarization of the reference and measuring waves are orthogonal, so the waves do not interfere with each other. Therefore, an additional electro-optic TE–TM converter serves to generate polarization components which can interfere. The further polarization splitter is used to separate the TE- and TM-polarized waves. A vibrating mirror at about 20 mm distance to the chip acts as object to be measured. Two PIN/FET detector/preamplifier modules are used as a single detector heterodyne receiver. The heterodyne signal was investigated by using an RF-spectrum analyzer. If operated with a vibrating mirror of sinusoidal oscillation $x(t) = x_o + A\sin(2\pi f_v t)$, different sidebands arise in the spectrum at multiples of f_v. The spectrum around the intermediate frequency of 171.08 MHz was measured with a 65 dB signal-to noise ratio using a spectrum analyzer resolution of 3 kHz.

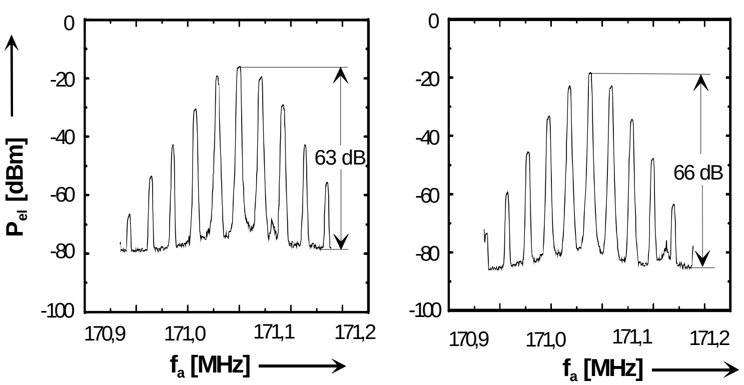

Fig. 3. Measured spectrum (3 kHz resolution) of the heterodyne interferometer signal for operation with a vibrating mirror at 20 kHz with detector of type FRM3Z121LT with bandwidth (100 MHz) (*left*) and detector of type FRM3Z621KT with bandwidth (400 MHz) (*right*).

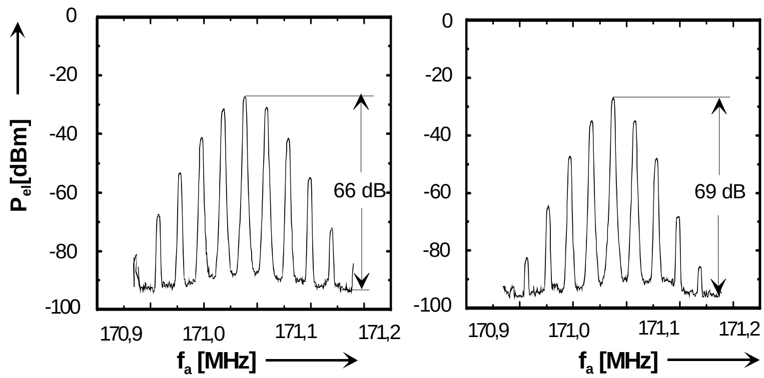

Fig. 4. Measured spectrum (3 kHz resolution) of the heterodyne interferometer signal for operation with a vibrating mirror at 20 kHz with balanced receiver of two detector of type FRM3Z121LT with bandwidth (100 MHz) (*left*) and detector of type FRM3Z621KT with bandwidth (400 MHz) (*right*).

The amplitude of the nth sideband is determined by the square of the nth Bessel function of the first kind J_n with argument $4A\pi/\lambda$ where λ is the wavelength of the DFB laser diode. Therefore, the amplitude A of the vibration can be determined by comparing the amplitudes of different sidebands (see Fig. 3).

To improve the signal-to-noise ratio two PIN-FET detector/preamplifier modules are used as a balanced receiver. This configuration gives the dual-detector receiver an advantage over the single detector heterodyne receiver. The advantage is the dual detector's ability to cancel local oscillator (LO) noise. The LO noise produced in each detector is in phase, while the IF beat signal in the two detector are 180° out of phase.

By subtracting the two photocurrents. The LO intensity noise can be suppressed. The resulting signal-to-noise ratio of the heterodyne signal shown to be better than with single-detector heterodyne receiver (see Fig. 4).

4. Conclusions

We have demonstrated a high performance integrated acousto-optical heterodyne interferometer for sensor applications. An acousto-optical TE–TM mode converter, two polarization beam splitter, three electro-optical TE–TM converters and two phase shifters have been integrated on a common substrate. Using an external DFB laser diode as a light source with 1561 nm emission wavelength the fully packaged interferometer gave a signal-to-noise ratio of 69 dB with balanced detection at 3 kHz bandwidth. The sensitivity of detectable amplitude is 105 pm.

The complex structure, large frequency bandwidth, high sensitivity and potential low insertion loss make the integrated heterodyne interferometer very attractive for a range of possible applications; vibration analysis of the amplitude of the oscillating cantilever of an atomic force microscope (AFM) is just one example.

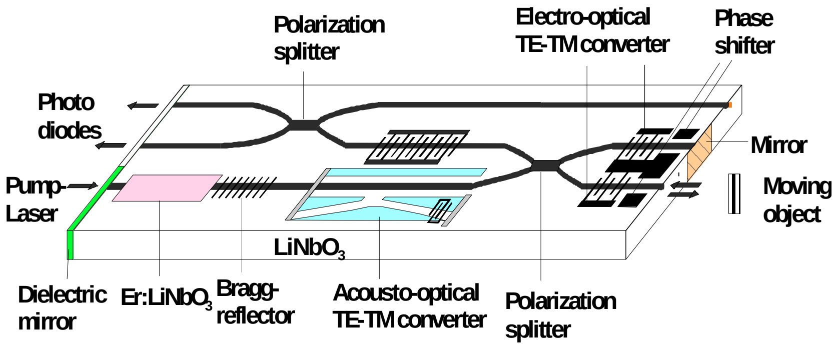

Fig. 5. Monolithic integration of the Ti:Er:$LiNbO_3$ DBR-waveguide laser.

It is planned to integrate the Er-diffusion-doped DBR-waveguide laser monolithically on the interferometer chip (see Fig. 5). An Er-diffusion-doped DBR-waveguide laser, pumped by a laser diode ($\lambda_p \sim 1480$ nm), is planned as integrated coherent light source with ~ 1530 nm emission wavelength.

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