Miniature 10 kHz thermo-optic delay line in silicon

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Received July 15, 2010; revised September 23, 2010; accepted September 24, 2010;
posted November 8, 2010 (Doc. ID 131789); published November 24, 2010

The scanning delay line is a key component of time-domain optical coherence tomography systems. It has evolved since its inception toward higher scan rates and simpler implementation. However, existing approaches still suffer from drawbacks in terms of size, cost, and complexity, and they are not suitable for implementation using integrated optics. In this Letter, we report a rapid scanning delay line based on the thermo-optic effect of silicon at $\lambda = 1.3 \mu\text{m}$ manufactured around a generic planar lightwave circuit technology. The reported device attained line scan rates of 10 kHz and demonstrated a scan range of 0.95 mm without suffering any observable loss of resolution (15 μm FWHM) owing to depth-dependent chromatic dispersion. © 2010 Optical Society of America

OCIS codes: 130.3120, 170.4500, 170.1650, 160.6840, 110.1650.

Different types of scanning delay lines have been reported in the history of optical coherence tomography (OCT). The most straightforward one is the galvanometer-mounted retroreflector [1], in which a simple mirror connected to a linearly scanning galvanometric device is used to provide a variable delay. This implementation, with line rates under 10 Hz, is too slow for real-time image acquisition. Fiber actuation by piezoelectric means was proposed as a faster replacement [2]. Typical acquisition rates are around 1 kHz, but some practical shortcomings plague this approach. Hysteresis, polarization mismatch, high voltages, and high power consumption are examples of the problems that impede wider adoption of these devices [3]. Another common solution is the grating-based delay line [4]. This device is based on a transformation of a time delay into a linear phase shift in the Fourier domain by means of a grating and a mirror with adjustable tilt. This embodiment typically provides up to 1 kHz without most of the problems appearing in the previous approaches. Disadvantages of grating-based delay lines are complexity, low stability over time, mechanical noise, power loss in the grating, and dispersion with broadband sources [5].

This Letter describes a chip containing a variable delay line produced making use of the thermo-optical effect of silicon. This effect consists of the modulation of the refractive index of the material with changing temperature. Taking into account the very high thermal diffusivity of silicon, reasonably fast devices can be produced [6]. Here we present the fabrication and characterization of such devices. Because they are compact, have no moving parts, and can be produced at a low cost, they offer great promise for simplifying the overall OCT instrumentation. Additionally, given that they are based on silicon photonics, their integration with passive couplers and other elements into full on-chip time-domain OCT systems is straightforward.

From the definition of group velocity (v_g), we can calculate the total group delay induced by a waveguide section of fixed physical length (l_0). Under a strong confinement assumption, we can expand the expression for the group delay in terms of the effective refractive index

of the waveguide (n_{eff}) and the one for the core material (n_{Si} , for silicon) according to Eq. (1):

$$\tau_g = \frac{l_0}{v_g} = l_0 \frac{d\beta}{d\omega} = \frac{l_0}{c} \left[n_{\text{eff}} + \omega \frac{\partial n_{\text{eff}}}{\partial \omega} + \omega \frac{dn_{\text{Si}}}{d\omega} \right]. \quad (1)$$

The evaluation of the thermo-optic effect can then be developed deriving the group delay with respect to temperature under the assumption of strong confinement. Numerical simulations done with beam-propagation-method software show that thermal changes in group delay mediated through the waveguide geometry are negligible. Under these conditions, $dn_{\text{eff}}/dT = dn_{\text{Si}}/dT$. Equation (2) summarizes the thermo-optic effect on the group delay:

$$\frac{d\tau_g}{dT} = \frac{l_0}{c} \left[\frac{dn_{\text{Si}}}{dT} + \omega \frac{d^2 n_{\text{Si}}}{d\omega dT} \right]. \quad (2)$$

In practice, according to published data for silicon at room temperature and $\lambda = 1.3 \mu\text{m}$ [7], this corresponds to an effective group thermo-optic coefficient of $dn_g/dT = 3.1 \cdot 10^{-4} \text{ K}^{-1}$ compared to a phase coefficient equal to $dn_{\text{Si}}/dT = 2.4 \cdot 10^{-4} \text{ K}^{-1}$.

The devices were produced using silicon-on-insulator (SOI) technology. To modulate the thermal properties of the devices, a membrane containing the wave guiding volume was micromachined. First, a monocrystalline intrinsic silicon layer was grown epitaxially to the thickness of 3 μm to meet the desired height of the rib. The waveguides were defined using optical lithography and an inductively coupled plasma (ICP) process was used to etch them. Silicon nitride was then deposited as a backside mask for the final bulk micromachining stage that results in the freestanding membranes. Platinum metal heaters were defined using a lift-off step, and a second metal layer (gold) was added for a parallel low-impedance driving of the heat-generating structure. Next, the backside mask is patterned to define the areas of the device layer that will be released. Finally, the wafer is etched in KOH from the back, making sure that the ribs and the heater

Fig. 1. (Color online) Fabricated chip with two individual delay stages mounted on a heat sink for thermal and optical characterization. The excitation and readout electronic board can be seen around it.

structures are protected. The BOX layer is used as an etch stop and is subsequently removed in 0.1% HF. A manufactured and packaged device is shown in Fig. 1.

To use the device as a variable delay line, its group delay should preferably change in a linear fashion. A triangular waveform was chosen as the ideal group-delay function to avoid discontinuities. The device is driven by an electrical signal. The transition from the applied voltage into a change in group delay incorporates parameters that are nonlinear in the thermal domain, such as thermal conductivity and diffusivity and the thermo-optic effect. Furthermore, the bandwidth of the device is known to be limited.

The excitation signal can be used to compensate for nonlinearities, and the bandwidth can be extended by pre-emphasizing its high-frequency components. The excitation signal is calculated offline using the iterative algorithm shown in Fig. 2. The starting point of the algo-

Fig. 2. Iterative algorithm used to find the excitation signal for a specific device to compensate for nonlinearities and to extend the bandwidth of the device.

Fig. 3. Frequency response of two membranes with dimensions $10 \text{ mm} \times 88 \mu\text{m}$ and $10 \text{ mm} \times 118 \mu\text{m}$ as measured using a small-signal sinusoidal excitation (symbols) and as computed from a linear model.

rithm is the quasi-static solution (V_0), a scaled square root of the triangular waveform. The excitation voltage signal (V_i) is fed through a set of equations that models the device. First, the power signal (P_i) is found through Joule's law. Second, a nonlinear partial differential equation solver gives the temperature distribution caused by Joule heating. From this distribution, one can find the average temperature along the waveguide (T_i). The actual temperature leads to a change in group delay (τ_{gi}) through the thermo-optic effect. Subsequently, the calculated group delay is compared to the ideal triangular waveform, resulting in an error function (ϵ_i). From the error function, the accuracy (ζ_i) is determined. If the specified accuracy is met, the final periodic excitation signal (V_{opt}) is found. Otherwise, the excitation signal is updated according to the time-dependent error function, and the sequence of nonlinear equations is evaluated again. Typical peak voltages of the excitation signals are in the range 30–40 V, depending on membrane width and desired scan range. The corresponding calculated temperature increases are $\Delta T = 60\text{--}90 \text{ K}$. These values

Fig. 4. Calibration graph of a delay line with a 1-cm-long and $88\text{-}\mu\text{m}$ -wide membrane in a single-pass configuration for 10 kHz line rate excitation. The scan associated with rising temperatures is noted with circles, and the one with falling temperature is noted with squares.

Fig. 5. Scan lines of a delay device with a 1-cm-long and 88- μm -wide membrane in a four-pass configuration as a function of the position of the reference mirror at a line rate of 2 kHz.

correspond to peak input powers of 11–20 W for a single stage.

Figure 3 shows the calculated and measured power-to-delay frequency response for two membrane widths (88 and 118 μm). The magnitude of all responses has been normalized to its low-frequency value to ease comparison of their frequency falloff. The threshold of 50% power-to-temperature conversion is crossed at frequencies well over 10 kHz (18 and 31 kHz for 118 and 88 μm , respectively) in the simulations. Yet the corresponding experimental values are only 4.5 and 7 kHz. Although these estimates of bandwidth might not be very accurate because of shift effects related to the normalization of the curves, it is clear that the membranes behave slower than the model predicts. This lower speed can be seen as a lower thermal diffusivity of the silicon in the membrane compared to the one for bulk silicon used in the calculations. Diffusion coefficients in thin membranes exhibit deviations from the properties of the bulk material [8]; except for the case of silicon, this effect was only important for low temperatures. Other possible explanations to this reduction in observed diffusivity are the role of the insulating silicon nitride film and geometrical model limitations.

Figure 4 shows the calibration curve for the device under the excitations computed as described above. It displays the computed scan position, against the physical position of the mirror as set by a stepper motor controller. The scan position is computed based on a linear time interpolation of the location of the maxima of the optical interference pattern. The sections of the waveform where temperature is rising and falling are separately considered and folded together by inverting the direction of the scan.

The curve displayed was computed from a collection ($N = 25$) of measured data; the standard deviation of the location of the maxima, visible as error bars in the figure, was obtained in this way. The device can be seen to provide similar scan curves for both scan directions and the results are reasonably linear. Under these conditions, the maximum errors in the upgoing and downgoing curves are 6 and 9 μm , respectively, corresponding to 3% and 4.5% of the full scan range. A slightly better behavior can be obtained for lower excitation frequencies as the limited bandwidth of the membrane plays a smaller role.

Figure 5 represents a scan obtained sending the light through the active region four times, which is achieved by means of partial reflection at the device interface, producing an effective active length of 4 cm. The graph is a representation of the raw optical data with the horizontal axis containing the temporal dimension and the vertical axis showing the physical position of a movable reference mirror. It shows 0.95 mm being scanned with a line rate of 2 kHz and good linearity. It is interesting to note that the system FWHM resolution was measured at 15 μm throughout the full scan range, corresponding to negligible scan-depth-dependent group-velocity dispersion for the used bandwidth (55 nm).

In conclusion, a rapid-scanning delay line for OCT based on integrated optics has been reported. The performance of the devices is sufficient for time-domain OCT, with line rates of 10 kHz and scan ranges of nearly 1 mm. We have further shown that depth-dependent chromatic dispersion did not limit system performance at 1.3 μm , making the presented approach a viable option for the generation of a fully integrated time-domain OCT system in silicon photonic platforms.

The authors thank the staff at the DIMES facility for support with device fabrication. This research has been funded by the Dutch technology foundation STW under contract 7505.

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