Miniature Thermo-Optic Delay Lines in Silicon

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The scanning delay line is a key component of time-domain optical coherence tomography systems. It has evolved since its inception towards higher scan rates and simpler implementation. In this paper we report a rapid delay line based on silicon working at 1.3 μm. A line scan rate of 10 kHz for a 200 μm scan range in air for carefully adjusted voltage waveform is demonstrated.

Introduction

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]. A simple mirror connected to a linearly scanning galvanometric device is used to provide a variable delay. This implementation, with line rates under 10Hz, is too slow for real-time image acquisition, cannot prevent motion artefacts and is bulky and difficult to maintain. For these reasons, it has been mostly abandoned. Fibre actuation by piezoelectric means was proposed as a faster replacement of the galvanometer retroreflectors [2]. This method is based on the change in group velocity in a fibre when it is stretched along its axis. Typical acquisition rates are around 1000 lines/second, but some practical shortcomings plague this approach. Hysteresis, polarisation mismatch, high voltages and high power consumption are examples of the problems that impede wider adoption of these devices [3].

Another very common solution for this component in the reference arm 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 1000 lines/second without most of the problems appearing in the previous approach. Disadvantages of grating based delay lines are complexity, low stability over time, mechanical noise, loss of optical power in the grating and chromatic dispersion with broadband sources [5].

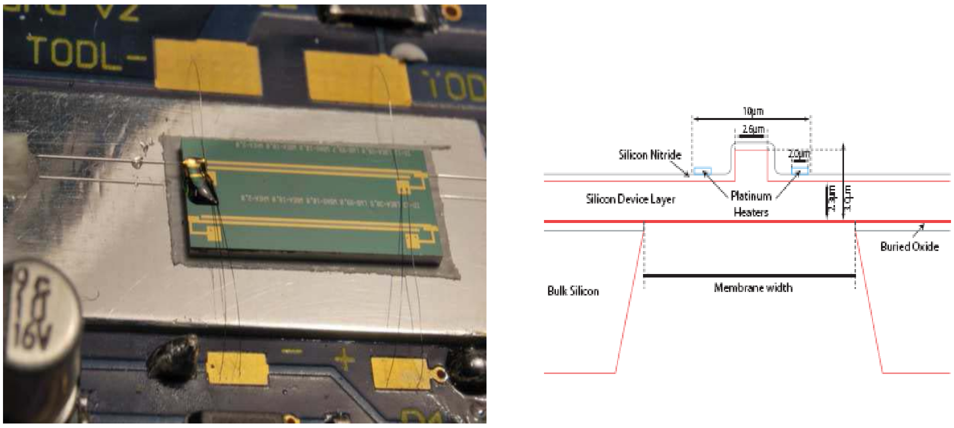
This article describes a chip containing a variable delay line produced making use of the thermo-optical effect of silicon. This effect consists of the significant modulation of the refractive index of the silicon bulk material with changing temperature. Taking into account the very high thermal diffusivity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

Delay Line Manufacturing

The devices have been fabricated making use of Silicon-On-Insulator (SOI) technology. The process starts with a standard SIMOX wafer with a buried oxide (BOX) of 375nm and a 200nm thick device layer. On top of it, the monocrystalline silicon layer is expanded to 3µm through epitaxial growth to meet the desired height of the rib waveguide. A 200nm thick thermal oxide is grown and patterned to produce the waveguide mask used in the reactive ion etching (RIE) process that defines the rib. A Cl2/HBr gas mixture with an Inductively Coupled Plasma (ICP) was used, obtaining a good etch uniformity over the wafer surface. The etch depth is set to 700nm. The oxidemask is then removed using HF. The next stage involves oxidation of the waveguides in order to reduce the surface roughness of the RIE vertical walls, which can cause very strong scattering losses [7]. It has been found that the growth and wet removal of ~400nm of SiO2 reduces this type of loss from > 30dB/cm to < 1dB/cm. The oxidation was carried out in a high temperature oven at 1100°C in a dry atmosphere and the oxidation time was adjusted according to the desired thickness. A LPCVD silicon-rich silicon nitride layer is then deposited on the wafer as a KOH backside mask for the final bulk micro-machining stage that produces the free-standing membranes. This type of SiN has been chosen because of its excellent mechanical properties [8]. This layer further serves to provide electrical isolation from the substrate to the heater structures and it acts as a spacer to prevent the light in the waveguide from interacting with the metallic heaters. At this stage, the metal heaters are defined using a lift-off recipe with a 150nm thick evaporated platinum layer. The heater is structured in sections connected in parallel. This makes the parasitic resistance of the conduction lines from the connection point to the actual heater section quite critical. In order to reduce this effect, a second metal layer has been added. For this layer, gold is used instead of platinum because of its lower resistance. The patterning of the gold layer, just like the platinum one, is done using an image reversal lift-off recipe. The next step involves patterning of the backside mask, in order to define the areas of the device layer that will be left floating as free-standing membranes. This is done using a carrier wafer and a thick resist layer on the front side in order to prevent scratches in the waveguides and heaters. Finally, the membranes are released making use of bulk micro-machining. The wafer is etched in KOH, using a single-sided holder that protects the front side with the ribs and the heater structures. A protective layer of thick (~5µm) PMMA-based spin resist (AR-PC 503), able to withstand KOH, is added for additional protection of the front side and to offer some mechanical support for the larger membranes. The BOX layer is used as an etch stop, and it is subsequently removed by wet etching. Figure 1 shows a top view of a delay line that is electrically and optically connected to the OCT. Also shown in Figure1 is a cross section view of the membrane.

Results

A TD-OCT system is used to compare the position of the interference pattern to the known position of a mirror for the whole scan range. The system is linear if the measured positions coincide with the actual positions. The measurement setup is represented schematically in Figure 2. By means of an iteration process, voltage excitation waveforms are generated that result in a supposedly linear behaviour. Figure 3 shows the excitation waveform generated with help of a non-linear model and shows the intensity measured at the balanced detectors. In the ideal case, Figure 3 b) would show a triangular waveform. Preliminary results show a maximum inaccuracy of 5µm for the rising flank of the waveform. The falling edge performs a little poorer with an inaccuracy up to 8µm. It can be concluded that the membrane heats up according to the model, but cools down slower than expected. This is confirmed by thermal measurements performed on the membrane. This effect is inherent to the device, as it has no active cooling mechanism, but could be compensated for.



a) b)

Figure 1. a) Photograph of one of the delay lines, showing the excitation fibre , the bond wires and the mechanical mounting; b) Cross section and dimensions of the delay line.

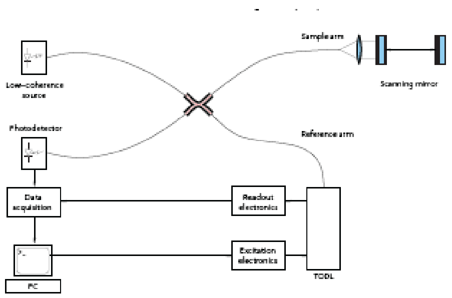
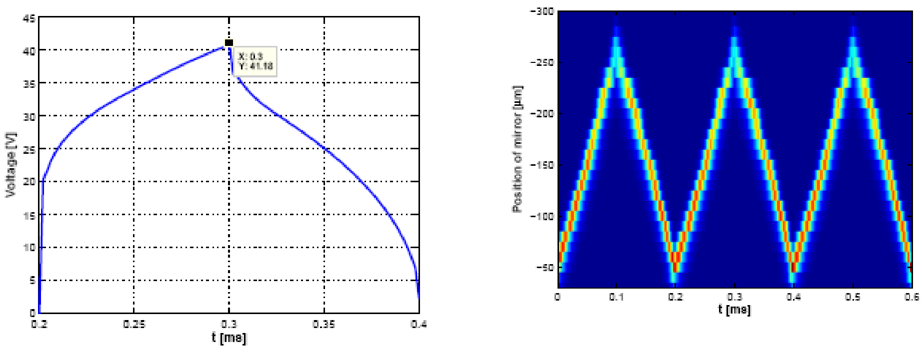


Figure 2. Schematic representation of the measurement set up.



a) b)

Figure 3. a) Excitation voltage waveform for a line scanning rate of 10kHz; b) Position of the interference pattern as a function of time. The line scanning rate is 10kHz with a scan range of ~200µm.

Conclusions

We have shown that thermo-optic delay lines can be actuated to yield excellent linearity and line scanning rates well in excess of the ones needed for surgical guidance applications, competing with the speed of FD-OCT with simple, inexpensive and compact components.

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