# Enabling acousto-optic devices for glass waveguides

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*We show numerically that surface acoustic waves, excited via a thin piezoelectric film on top of a buried waveguide, can induce a refractive index change in low-loss TriPleX ($Si_3N_4$) waveguides. The effect is sufficient to allow full light modulation using a balanced Mach-Zehnder interferometer.*

## Introduction

Glass based waveguides have become of great interest recently. Suitable for Lab-On-Chip applications, guiding visible light and ultra low-loss propagation [1, 2, 3], silicon nitride waveguide cores embedded in a silicon dioxide cladding presents a very flexible platform. To obtain index tunable waveguide components which are necessary for many applications, the advantages of glass-based waveguides need to be combined with active control of the effective refractive index such as for resonators, filters or Mach-Zehnder interferometers. Active control of the effective refractive index has been achieved in the past by using the thermo-optic effect, applying external heat. This technique is easy to implement but has the drawback of slow response, large power consumption and the necessity to disipate the heat.

Here we demonstrate the use of strain to induce dynamical changes in the effective refractive index experienced by the guided light. When such changes take place in one branch of a Mach-Zehnder interferometer (MZI), a phase shift with respect to the second branch of the MZI. This phase shift allows to modulate and switch light [9]. In comparison with thermally induced refractive index changes, the strain-optic effect allows much higher modulation frequency as well as much lower power consumption. Of particular relevance are buried waveguides because they provide lowest loss and highest protection from external perturbations.

An interesting way to induce strain in buried waveguides is to apply surface acoustic waves (SAWs)[5]. The advantages versus static methods it that strain can be focused to desired locations via constructive interference of multiple strain sources in the form of so-called interdigitized transducers (IDTs).

The excitation of surface acoustic waves requires *crystalline* materials because only these materials provide a sizable piezoelectric response. Accordingly, SAWs have been demonstrate in various crystalline materials [5, 6, 4]. The amorphous materials in which we are interest here ($Si_3N_4$ with $SiO_2$ cladding) show no own piezoelectric response. Therefore,

the excitation of SAWs requires the fabrication of crystalline, piezoelectric films on top of the amorphous $SiO_2$ cladding.
Here we model for the first time the modulation of guided light by SAWs in an amorphous, buried waveguide for the fabrication of an according sample.

## Strain-optic effect

When a material is subjected to strain, the infinitesimal volume elements of the material experience a local displacement from their static or rest positions. This confines the electrons either more tightly or more loosely depending on whether the strain is compressive or tensile. In anisotropic media, the changes in the relative permittivity of the material have to be expressed as a tensor equation[12],

$$\left[\Delta\left(\varepsilon^{-1}\right)\right]_{ij} = \sum_{kl} p_{ijkl} S_{kl}, \tag{1}$$

where $(\varepsilon^{-1})_{ij}$ is the dielectric tensor, $S_{kl}$ is the strain tensor and $p_{ijkl}$ are the strain-optic coefficients. For small changes in $(\varepsilon^{-1})_{ij}$, considering isotropic media such as amorphous materials, the tensor equation (1) can be simplified as,

$$\Delta n_i = \frac{1}{2} n_i^3 (p_{11} S_i + p_{12}, (S_j + S_k)), \tag{2}$$

where $n_i$ is the refractive index for linear polarization along the $i$ direction, where $i, j, k$ equals $x, y$ and $z$, and $S_j$ and $S_k$ are the cartesian components of the strain vector[7]. The index changes, $\Delta n$, for linear polarization in the others directions, *j* and *k*, are obtained by permutation of the indices.

## Surface acoustic waves and index modulation

Among surface acoustic waves, Rayleigh acoustic waves are the type of waves that we are interested to generate. This type of SAW propagates along the interface of two materials, has low propagation damping and a penetration depth in the order of half the acoustic wavelength in the material [5]. The penetration depth of the acoustic wave has to be chosen such that a sufficient amount of strain is present within the area of the buried waveguide where the optical mode is propagating. The acoustic wavelength is given by, $\lambda_{SAW} = v_{SAW}/f_{SAW}$, where $f_{SAW}$ is the chosen driving frequency. The propagation velocity of SAWs, $v_{SAW}$, is given by Young modulus, Poisson modulus and density of the various materials involved.
The velocity depends also on the thickness of the various layers, including piezoelectric layers, buffer layers, and surface electrodes for the IDT structure.
The structure that we consider for our modeling consists of a 27 nm high and 4.4 $\mu$m wide $Si_3N_4$ core buried 8 $\mu$m under the surface of a 16 $\mu$m thick silicon dioxide film. On the silicon dioxide surface we assume a 10 nm thick platinum layer covered with a 2 $\mu$m thick film of c-oriented PZT (crystalline piezo-material) followed by 100 nm thick metallic interdigitized platinum electrodes with a lateral period in the range from 20 to 80 $\mu$m.
Fig.1 shows a cross section through the structure superimposed with the intensity profile of the guided $TM_{00}$ mode as calculated from the Maxwell equations using an eigenmode method. In Fig.2 the fundamental surface acoustic mode is shown for a period

of 44 $\mu$m, calculated using a piezoelectric eigenmode solver using periodic boundary conditions[13]. The propagation direction of the SAW is perpendicular to the propagation of the optical mode. The results were confirmed with finite element calculations in the time domain[13].

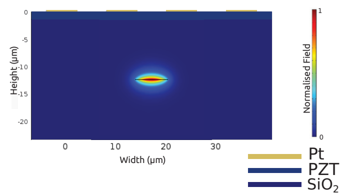


**Figure 1:** Cross section of the waveguide and IDT structure. The intensity distribution cross section of the $TM_{00}$ for 840 nm wavelength is superimposed. All shown features are to scale.

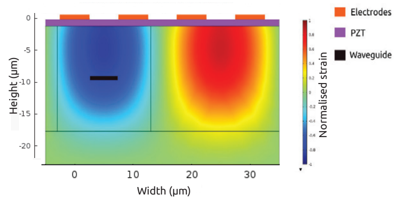


**Figure 2:** Cross section of calculated strain distribution of the fundamental surface acoustic wave, displayed over one acoustic wavelength. The size of the waveguide and IDTs are exaggerated for clarity.

Using the described model, we calculated the shape and effective refractive index, $n_{eff}$, of the waveguide mode $TM_{00}$ for the maximum and minimum strain. The calculations were carried out for a given driving voltage, 6 V, and the IDT period was varied in steps of 6 $\mu$m while varing the drive frequency accordingly for resonant excitation. The results are summarized in Figs.3 and 4. It can be seen that with the given parameters dynamical refractive index changes, $\Delta n_{eff}$, in the order of $10^{-3}$ to $10^{-4}$ should be achievable.

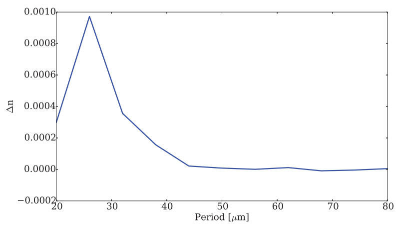


**Figure 3:** $\Delta n_{eff}$ of the $TM_{00}$ mode in the waveguide for a wavelength of 840 nm as a function of the acoustic wavelength, at a driving voltage of 6 V.

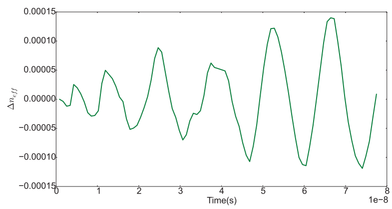


**Figure 4:** Dynamical evolution of the effective refractive index for an IDT period 44 $\mu$m excited with 73.4 MHz.

## Fabrication

The deposition of crystalline piezoelectric material on amorphous substrates was done with a large area pulsed laser deposition tool, or PLD, where a target with the material to deposit is ablated by high power laser pulses. During the process the wafer is kept at a temperature of $600^{o}$C. The deposition was performed by Solmates BV who is capable of depositing (001) textured $PbZiTiO_3$ (PZT) with a thickness homogeneity better than 5% with this technique. This deposition bears additional complexity in that a buffer layer between the amorphous material and the crystalline material needs to be deposited to achieve the right crystalline orientation of PZT. The buffer layer consists of a platinum coating on top of which a $LaNiO_3$ layer of 10 nm is deposited which seeds the crystalline growth of the PZT film with the C-axis normal to the surface. This orientation of the C-axis is required for maximizing the piezoeletric response, for maximizing the excitation of surface acoustic waves.

Finally, a 100 nm thin layer of platinum of Pt was deposited to optimize adhesion, and to provide electrical and mechanical contact, of the interdigitized electrode pattern. Fig.5 shows a microscope photograph of the top surface with the IDT electrodes. The fabricated samples show a homogeneous piezoelectric film thickness and high smoothness. First tests with a DC voltage show the absence of shortcuts in the electrode pattern. Next experimental steps include the application of RF signals while optically monitoring phase changes of light guided through the acoustic waveguide.

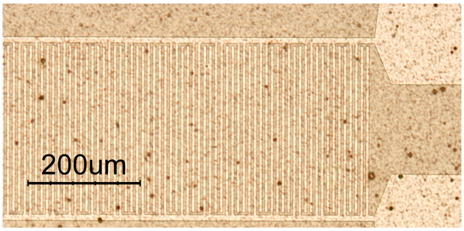


**Figure 5:** Fabricated IDTs on a waveguide chip

## Conclusions

We have shown with modeling that surface acoustic waves launched via a thin film of PZT material driven with a low voltage RF signal applied to interdigitized electrodes can be used for acoustic-optic modulation in buried silicon nitride/glass waveguides. The calculated effective index change, in the order of $10^{-3}$ to $10^{-4}$ corresponds to a phase shift of $\pi$ within a propagation length of 1 to 10 mm for near infrared radiation. Exploiting such phase shift in a Mach-Zehnder interferometer would allow full amplitude modulation with an arm length in that range. To prepare an experimental demonstration we have fabricated an according acousto-optic waveguide structure that is currently subjected to experimental characterization.

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## References

[1] R.G. Heideman, Proceedings Symposium IEEE, Benelux Chapter, 2005
[2] R.G. Heideman, Photonic West, Invited, 2009
[3] K. Zinoviev, Advances in Optical Technologies, **2008**, 383927, 2008
[4] S.H. Wemple, Phys. Rev., **1**, 193, 1970
[5] M. M. Lima, Rep. Prog. Phys. **68**, 1639-1701, 2005
[6] Shoji Kakio, Japanese Journal of Appl. Phys., **51**, 07GC12, 2012
[7] N.F. Borrelli and R.A. Miller, Appl. Opt., **7**, 745, 1967
[8] Colin K. Campbell, Surface Acoustic Wave Devices
[9] R.Syms, Optical Guided Waves and Devices, 1992
[10] S.H.Wemple, Phys. Rev. B, **1**, 1, 1969
[11] I.Kanno et al., Appl. Phys. Lett. **70**, 1378, 1997
[12] Robert Boyd, Nonlinear Optics 2nd Ed., 2003
[13] Comsol Multiphysics