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RPPR Final Report
as of 01-Nov-2017

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Agreement Number: W911NF-12-1-0488

INVESTIGATOR(S):

Name: Ph.D. Ronald M. Reano

Email: reano.1@osu.edu

Phone Number: 6142477204

Principal: Y

Organization: **Ohio State University**

Address: 1960 Kenny Road, Columbus, OH 432101016

Country: USA

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Title: RF Energy Interaction With Electro-Optic Materials (Single investigator award proposed to address research topic area 6.4. Electromagnetics and RF Circuit Integration)

Begin Performance Period: 28-Sep-2012

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Submitted By: Ph.D. Ronald Reano

Email: reano.1@osu.edu

Phone: (614) 247-7204

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STEM Degrees: 2

STEM Participants: 2

Major Goals: This project will capitalize the remarkable properties of hybrid ferroelectric and semiconductor materials. Under the framework of hybrid materials, unique opportunities are created to not only access some of the most surprising properties of materials but also to explore their interaction with RF energy to advance and develop a new class of radio frequency (RF)-optical devices and systems with unprecedented performance. The project brings together research concepts from RF engineering, optical physics, and material science allowing for both fundamental science and technological applications to be advanced in tandem. The goals of the research are threefold. First, the project focuses on the fundamental analysis and design of structures that couple RF and optical electromagnetic fields in a hybrid material system consisting of silicon and lithium niobate.

A hybrid material system consisting of both silicon and lithium niobate enables compact integrated optics on a silicon platform with electro-optic functionality provided by a true second order material susceptibility. We analyze the fundamental interaction of an RF electric field with an optical electric field in the hybrid material system.

Structures that effectively couple RF and optical electromagnetic fields are designed and analyzed using analytical and numerical techniques. Second, the project focuses on the fabrication of RF-optical coupling structures in the hybrid material system. Micrometer and nanometer scale fabrication techniques are created to realize structures that couple RF and optical electric fields in the silicon and lithium niobate hybrid material system. We develop methods to bond thin films of lithium niobate to patterned silicon. Metal films are used to concentrate the RF electric field in the vicinity of the optical electric field. Structures that effectively couple RF and optical electromagnetic fields are fabricated and evaluated under test and measurement. Third, the project focuses on RF-optical test and measurement demonstration vehicles. Test and measurement of fabricated structures will be conducted to experimentally quantify RF and optical performance. Measurement results will be compared with existing technologies and predictions from electromagnetic simulation.

Accomplishments: Please see the attached pdf document.

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Training Opportunities: One graduate student (Li Chen) and one undergraduate student (Jiahong Chen) received training related to RF and Optical technologies in a University Research Environment. The graduate student learned electromagnetic theory related to guided waves at both gigahertz frequencies and optical frequencies. The graduate student also was trained in advance nanoscale fabrication techniques for the development of coupled RF and optical structures. Both the graduate student and the undergraduate student were trained in conducting precision optical and RF measurements in the laboratory. The graduate student earned a PhD degree from this research project and the undergraduate student earned research experience during his senior year in undergraduate studies. Both students were trained to write documents for the purpose of archiving research results in technical journals.

Results Dissemination: Five journal papers and five conference papers have been published based on the research conducted for this project. The journal paper citations are:

1. L. Chen, J. Nagy, and R. M. Reano, "Patterned ion-sliced lithium niobate for hybrid photonic integration on silicon," *Optics Materials Express* 7, 2460-2467 (2016).
2. L. Chen, J. Chen, J. Nagy, and R. M. Reano, "Highly linear ring modulator from hybrid silicon and lithium niobate," *Optics Express* 23, 13255-13264 (2015).
3. L. Chen, M. Wood, and R. M. Reano, "Compensating thermal drift of hybrid silicon and lithium niobate ring resonances," *Optics Letters* 40, 1599-1602 (2015).
4. L. Chen, Q. Xu, M. Wood, and R. M. Reano, "Hybrid silicon and lithium niobate electro-optical ring modulator," *Optica* 1, 112-118 (2014).
5. Li Chen, Michael G. Wood, and Ronald M. Reano, "12.5 pm/V hybrid silicon and lithium niobate optical microring resonator with integrated electrodes," *Optics Express* 22, 27003-27010 (2013).

The conference paper citations are:

1. L. Chen, J. Nagy, and R. M. Reano, "(Invited) Patterning of Ion-Sliced Lithium Niobate for Hybrid Photonic Integration on Silicon," in *Conference on Lasers and Electro-Optics, 2016 OSA Technical Digest (online)* (Optical Society of America, 2016), paper SF1P.5.
2. L. Chen, J. Chen, J. Nagy, and R. M. Reano, "Hybrid Silicon and Lithium Niobate Racetrack Modulator with Large Spurious Free Dynamic Range," in *Conference on Lasers and Electro-Optics, 2015 OSA Technical Digest (online)* (Optical Society of America, 2015), paper STu2F.5.
3. L. Chen, M. G. Wood, and R. M. Reano, "Low Power Compensation of Thermal Drift in Hybrid Silicon and Lithium Niobate Ring Resonators," in *Frontiers in Optics, 2015 OSA Technical Digest (online)* (Optical Society of America, 2015), paper FTh3B.4.
4. L. Chen, Q. Xu, M. Wood, and R. M. Reano, "Gigahertz microring electro-optical modulator in hybrid silicon and lithium niobate," in *Frontiers in Optics, OSA Annual Meeting* (Optical Society of America, 2014), paper FTu1D.3.
5. L. Chen, M. Wood, and R. M. Reano, "Low Tuning Voltage Hybrid Silicon and Lithium Niobate Optical Microring Resonator with Integrated Electrodes," *Conference on Lasers and Electro-Optics (CLEO), San Jose, California* (2013).

Honors and Awards: Two papers from this research project received Outstanding Journal Article Awards at the Electroscience Laboratory, Department of Electrical and Computer Engineering, The Ohio State University.

1. L. Chen, J. Chen, J. Nagy, and R. M. Reano, "Highly linear ring modulator from hybrid silicon and lithium niobate," *Optics Express* 23, 13255-13264 (2015).
2. L. Chen, M. G. Wood, and R. M. Reano, "12.5 pm/V hybrid silicon and lithium niobate optical microring resonator with integrated electrodes," *Optics Express* 22, 27003-27010 (2013).

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Protocol Activity Status:

Technology Transfer: The research results generated one patent application filed with the United States Patent and Trademark Office through the Ohio State University. The patent application is titled "Patterned ion-sliced crystal for hybrid integrated photonics" by Ronald M. Reano and Li Chen. In the patent application is described a method of forming a deterministic thin film from a crystal substrate. The method can include implanting ions into a surface of the crystal substrate to form a thin film crystal layer, and bonding the crystal substrate and a handle substrate to form a bilayer bonding interface between the crystal substrate and the handle substrate. The method can also include exfoliating the thin film crystal layer from the crystal substrate, patterning the thin film crystal layer to define a deterministic thin film, etching one or more trenches in the thin film crystal layer, etching the bilayer bonding interface via the one or more trenches, and releasing the deterministic thin film from the handle substrate. The technology is enabling for future hybrid integrated photonic systems for communications, computing, and sensing.

PARTICIPANTS:

Participant Type: PD/PI

Participant: Ronald M Reano

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Li Chen

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Undergraduate Student

Participant: Jiahong Chen

Person Months Worked: 6.00

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Other Collaborators:

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Materials Express
Publication Identifier Type: DOI **Publication Identifier:** <https://doi.org/10.1364/OME.6.002460>
Volume: 6 **Issue:** 7 **First Page #:** 2460
Date Submitted: 9/22/17 12:00AM **Date Published:** 7/1/16 4:00AM
Publication Location:

Article Title: Patterned ion-sliced lithium niobate for hybrid photonic integration on silicon

Authors: Li Chen, Jonathan Nagy, Ronald M. Reano

Keywords: Integrated optics materials; Lithium Niobate; Integrated optics devices; Electro-optical devices; Resonators.

Abstract: A method to realize patterned ion-sliced lithium niobate is presented for hybrid photonic integration on silicon. The process involves indirect wafer bonding and dry etching to produce patterns with controllable size, shape, and orientation. The patterns are released by sacrificial wet etching and transferred to silicon waveguides using a pick-and-place process. To demonstrate the technique, a hybrid silicon and lithium niobate racetrack resonator with co-planar electrodes is presented with a measured tunability of 5.2 pm/V. The method enhances flexibility in design and control of fabrication yield for the realization of hybrid silicon and lithium niobate integrated optic devices.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Optics Express
Publication Identifier Type: DOI **Publication Identifier:** 10.1364/OE.23.013255
Volume: 23 **Issue:** 10 **First Page #:** 13255
Date Submitted: 9/22/17 12:00AM **Date Published:** 5/1/15 4:00AM
Publication Location:

Article Title: Highly linear ring modulator from hybrid silicon and lithium niobate

Authors: Li Chen, Jiahong Chen, Jonathan Nagy, Ronald M. Reano

Keywords: Integrated optics devices; Electro-optical devices; Modulators; Resonators; Lithium niobate; Radio frequency photonics.

Abstract: We present a highly linear ring modulator from the bonding of ion-sliced x-cut lithium niobate onto a silicon ring resonator. The third order intermodulation distortion spurious free dynamic range is measured to be 98.1 dB Hz^{2/3} and 87.6 dB Hz^{2/3} at 1 GHz and 10 GHz, respectively. The linearity is comparable to a reference lithium niobate Mach-Zehnder interferometer modulator operating at quadrature and over an order of magnitude greater than silicon ring modulators based on plasma dispersion effect. Compact modulators for analog optical links that exploit the second order susceptibility of lithium niobate on the silicon platform are envisioned.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
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Volume: 40 **Issue:** 7 **First Page #:** 1599
Date Submitted: 9/22/17 12:00AM **Date Published:** 3/1/15 5:00AM
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Article Title: Compensating thermal drift of hybrid silicon and lithium niobate ring resonances

Authors: Li Chen, Michael G. Wood, Ronald M. Reano

Keywords: Integrated optics devices; Sensors; Lithium niobate; Resonators; Optical interconnects.

Abstract: We present low-power compensation of thermal drift of resonance wavelengths in hybrid silicon and lithium niobate ring resonators based on the linear electro-optic effect. Fabricated devices demonstrate a resonance wavelength tunability of 12.5 pm/V and a tuning range of 1 nm. A capacitive geometry and low thermal sensitivity result in the compensation of 17°C of temperature variation using tuning powers at sub-nanowatt levels. The method establishes a route for stabilizing high-quality factor resonators in chip-scale integrated photonics subject to temperature variations

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Conference Name: CLEO: Science and Innovations
Date Received: 22-Sep-2017 Conference Date: 09-Jun-2013 Date Published: 09-Jul-2013
Conference Location: San Jose, California
Paper Title: Low Tuning Voltage Hybrid Silicon and Lithium Niobate Optical Microring Resonator with Integrated Electrodes
Authors: Li Chen, Michael Wood, Ronald M. Reano
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Frontiers in Optics
Date Received: 22-Sep-2017 Conference Date: 19-Oct-2014 Date Published: 19-Oct-2014
Conference Location: Tucson, Arizona
Paper Title: Gigahertz Microring Electro-Optical Modulator in Hybrid Silicon and Lithium Niobate
Authors: Li Chen, Qiang Xu, Michael Wood, Ronald M. Reano
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Frontiers in Optics
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Conference Location: San Jose, California
Paper Title: Low Power Compensation of Thermal Drift in Hybrid Silicon and Lithium Niobate Ring Resonators
Authors: Li Chen, Michael G. Wood, Ronald M. Reano
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
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Conference Location: San Jose, California
Paper Title: Hybrid Silicon and Lithium Niobate Racetrack Modulator with Large Spurious Free Dynamic Range
Authors: Li Chen, Jiahong Chen, Jonathan Nagy, Ronald M. Reano
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Conference Name: CLEO: Science and Innovations
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Paper Title: Patterning of Ion-Sliced Lithium Niobate for Hybrid Photonic Integration on Silicon
Authors: Li Chen, Jonathan Nagy, Ronald M. Reano
Acknowledged Federal Support: **Y**

DISSERTATIONS:

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Title: Hybrid Silicon and Lithium Niobate Integrated Photonics

Authors: Li Chen

Acknowledged Federal Support: Y

PATENTS:

Intellectual Property Type: Patent

Date Received: 22-Sep-2017

Patent Title: Patterned ion-sliced crystal for hybrid integrated photonics

Patent Abstract: An example method of forming a deterministic thin film from a crystal substrate is described

Patent Number: 15/612,087

Patent Country: USA

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Application Status: 1

Date Issued:

SECTION: ACCOMPLISHED UNDER GOALS WITH FIGURES AND REFERENCES

A. DESIGN.

We have designed structures on the micro-scale to efficiently couple RF and optical energy in the hybrid silicon and lithium niobate material system. A schematic of a tunable hybrid silicon and lithium niobate (LiNbO_3) microring resonator is shown in Fig. 1(a). The resonator consists of a silicon rib waveguide microring and a LiNbO_3 thin film bonded to the silicon resonator as a portion of the top cladding via BCB. The silicon rib waveguides are 500 nm wide with a 70 nm slab thickness and 180 nm rib height. A bottom metal electrode is formed around and exterior to the microring on the silicon slab to provide an electric path to the silicon core. A top metal electrode is aligned to the microring on top of the LiNbO_3 thin film and a SiO_2 buffer layer that is deposited by plasma enhanced chemical vapor deposition (PECVD). Figure 1(b) shows a schematic of the cross-section of the device structure.

The LiNbO_3 thin film and the PECVD SiO_2 buffer layer serve as the top cladding. On the cross-section of the microring waveguide, a portion of the optical guided-mode is within the LiNbO_3 thin film. Figure 2(a) shows the fraction of the optical mode power within the LiNbO_3 thin film as a function of the thickness of the LiNbO_3 thin film for the transverse electric (TE) and transverse magnetic (TM) modes, at 1550 nm optical wavelength, calculated using the semi-vector beam propagation method (BPM). In the simulation, the PECVD SiO_2 layer below the aluminum electrode is set to be 1 μm thick. The refractive indices of silicon, SiO_2 , LiNbO_3 and BCB are set to 3.48, 1.44, 2.14 and 1.54, respectively, in the simulation. The maximum fraction of the optical mode power in the LiNbO_3 approaches 42% for the TM mode and 11% for the TE mode as the LiNbO_3 thickness approaches 1 μm . The larger optical mode field overlap with the LiNbO_3 for the TM mode is desirable for greater tuning efficiency. Moreover, the TM mode accesses the r_{33} electro-optic coefficient in LiNbO_3 , whereas the TE mode accesses the r_{13} electro-optic coefficient ($r_{33} = 31 \text{ pm V}^{-1}$, $r_{13} = 8 \text{ pm V}^{-1}$ in bulk LiNbO_3) [1,2]. Therefore, the device is designed for the TM mode. Furthermore, the fraction of the optical mode power in the LiNbO_3 for the TM mode is marginally improved for LiNbO_3 thicknesses greater than 600 nm. The thickness of the LiNbO_3 is therefore chosen to be 800 nm.

The use of the silicon microring as a transparent conductor minimizes the dielectric layer thickness required to isolate the optical mode from the electrodes [3]. As a result, the voltage induced electric field inside the LiNbO_3 cladding layer is enhanced thereby enabling a larger change in the refractive index of the LiNbO_3 via the linear electro-optic effect. The PECVD SiO_2 cladding layer thickness significantly influences the electric field intensity in the LiNbO_3 ($\epsilon_z = 29.1$) [1] thin film since the permittivity of LiNbO_3 is much higher than that of PECVD SiO_2 (relative permittivity $\epsilon_r = 4.2$) [4]. The red curve in Fig. 2(b) shows the vertical (perpendicular to the surface of the substrate) electric field intensity (E_z) of the applied DC field in the LiNbO_3 thin film as a function of the PECVD SiO_2 thickness simulated using the finite element method (FEM) electro-static solver. The electric field distribution within LiNbO_3 is not uniform due to the rib topology of the silicon waveguide. Therefore, the electric fields are evaluated at the center of the LiNbO_3 thin film directly above the center of the silicon waveguide. For an 800 nm thick LiNbO_3 thin film and an applied voltage of 1 V between the top electrode and the silicon core, E_z in the LiNbO_3 thin film decreases from 1.15 V/ μm to 0.45 V/ μm as the PECVD SiO_2 layer increases from 0 nm to 300 nm.

A thinner PECVD SiO_2 layer is desirable for achieving higher electric field in LiNbO_3 . Conversely, reducing the PECVD SiO_2 thickness leads to optical loss from the optical mode interacting with the top aluminum electrode. The blue curve in Fig. 2(b) shows the TM mode optical loss caused by the aluminum electrode at 1550 nm wavelength, as a function of the PECVD SiO_2 thickness, calculated by BPM. In the simulation, the imaginary part of the refractive index of aluminum is set to 16 [5]. The thickness of the PECVD SiO_2 layer is chosen to be 125 nm. Relatively large electric fields in the LiNbO_3 and metal-induced optical loss less than 0.2 dB/cm are expected.

Figure 3(b) shows the cross-section electric field distribution of the design for the fundamental TM mode at 1550 nm optical wavelength calculated using BPM. Material boundaries are indicated by the white dashed lines and the material regions are indicated in the insets. The BCB thickness is 0 nm in the simulation. The effective index is calculated to be 2.3.

A second design that focuses on high frequency performance and the utilization of the transverse electric (TE) mode is shown in Fig. 4. The cross-section is through the center of the ring resonator. The device consists of a 15 μm radius silicon rib waveguide ring and a one micrometer thick z-cut ion-sliced LiNbO_3 thin film bonded via BCB [6]. The rib waveguides are 500 nm wide with a 45 nm slab thickness and 205 nm rib height. The silicon slab is patterned so that it exists only around and exterior to the ring. The silicon core and surrounding silicon slab layer are doped to function as a transparent conductor with reduced series resistance [7]. A voltage applied between the top electrode and the bottom electrode produces an electric field confined between the top electrode and the silicon waveguide core.

The 1550 nm wavelength TE optical mode distribution is shown in Fig. 5 calculated by BPM. The effective index of the optical mode is 2.66. Also shown is the voltage induced electric field (yellow vectors) from a DC voltage applied between the top electrode and the silicon transparent conductor, using material permittivities in finite element method calculations [8,9,10].

The optical mode and the electric field vectors overlap in the LiNbO_3 . The fraction of the optical mode power in the LiNbO_3 is 11%. The TE mode accesses the r_{13} electro-optic coefficient in LiNbO_3 ($r_{13} = 8 \text{ pm V}^{-1}$ in bulk LiNbO_3) [9] and takes advantage of the nearly vertical voltage induced electric field in the LiNbO_3 .

The device speed is limited by the RC time constant and the photon lifetime in the ring resonator [11]. The electrical resistance originates primarily from the silicon transparent conductor and the contact resistance. To reduce the resistance, the silicon waveguide is blanket implanted with P-type dopants at a light dose, followed by a P-type heavy dose on the slab. The heavily-doped region is 300 nm away from the silicon core to avoid excessive optical loss.

The two previous designs utilized z-cut lithium niobate. In the third design, x-cut lithium niobate is utilized in order to incorporate co-planar electrodes. A schematic of the hybrid silicon and LiNbO_3 structure is shown in Fig. 6. The device consists of a silicon strip waveguide ring resonator and a 1 μm thick x-cut ion-sliced LiNbO_3 thin film bonded via BCB [12]. The ring radius is 10 μm on the curves and is 50 μm in length on the straight sections. The cross-section of the silicon strip waveguide is 550 nm $\times$ 170 nm and the coupling gap between the bus waveguide and the ring is 180 nm. The z crystal axis of the LiNbO_3 is oriented perpendicular to the propagation direction of the straight sections of the ring.

Metal electrodes are placed on top of the LiNbO_3 thin film with a 1 μm lateral electrode gap aligned to the center of the silicon core. The electrodes are interdigitated so that the directions of the applied electric fields in the two straight waveguide sections are the same. As a result, the phase change accumulates constructively as light propagates along the racetrack ring. The configuration allows the device to access the r_{33} electro-optic coefficient along the straight waveguide sections for the transverse-electric (TE) optical waveguide mode. A large ratio of straight section length to curved section length around the ring is desirable because the modulation efficiency is weaker along the arcs.

Figure 7 shows the TE mode optical distribution in a straight waveguide section at 1550 nm calculated via the beam propagation method. The mode effective index is 2.45 and the fraction of the optical mode power in the LiNbO_3 is 25%. Also shown is the electric field (yellow vectors) from a DC voltage applied between the top metal electrodes. The high optical confinement allows the top side metal electrodes to be placed close to each other and over the waveguide without inducing large optical absorption loss, enabling a large electric field for a given applied voltage. The capacitance per unit length of the electrode is calculated to be 0.2 pF/m based on finite element method simulations. A device capacitance of 30 fF and resistance of 30 Ω yields an RC limited bandwidth of 66 GHz in a 50 Ω system. As a result, the device speed is limited by the photon lifetime of the resonator.

B. FABRICATION

In this phase of the research, a method was developed to produce patterned thin films of ion-sliced LiNbO_3 for hybrid photonic integration on silicon. Thin films of LiNbO_3 with deterministic shape and crystal orientation are obtained with edge lengths in the range of hundreds of microns to several millimeters. The patterned LiNbO_3 thin films are transferred and bonded to silicon waveguides using a pick-and-place process [13]. Patterning allows the crystal axes of LiNbO_3 to be identified for electrode orientation.

The process to obtain patterned ion-sliced LiNbO_3 is illustrated in Fig. 8 using x-cut LiNbO_3 wafers as an example. A 3-inch x-cut LiNbO_3 wafer of 500 μm thickness is diced into rectangular samples with edge lengths ranging from 0.5 cm to 3 cm. The x-cut LiNbO_3 sample is implanted with He^+ ions with an implantation energy of 380 keV and a fluence of 3.5×10^{16} ions cm^{-2} , as shown in Fig. 8(a). During ion implantation, Ag paste is applied between the LiNbO_3 sample and the sample holder to enhance thermal dissipation. The beam current density is maintained at 0.25 $\mu\text{A cm}^{-2}$ and the total implantation time is seven hours. The temperature of the wafer holder increases gradually during the implantation but remains below 100 $^\circ\text{C}$.

After ion implantation, the LiNbO_3 sample is cleaned using RCA1 solution and clad with 1 μm of plasma enhanced chemical vapor deposition (PECVD) SiO_2 . The PECVD SiO_2 layer will serve as a sacrificial layer to release the ion-sliced LiNbO_3 later in the process. A second x-cut LiNbO_3 handle wafer is cleaned with RCA1 and coated with adhesion promoter (Dow Chemical AP3000) and BCB (Dow Chemical CYCLOTENE 3022-35), as shown in Fig. 8(b). The implanted wafer is coated with adhesion promoter and bonded to the LiNbO_3 handle wafer via the BCB film. The crystal z axes of the wafers, which are along the edges of the wafers, are aligned to each other under a microscope. The bonded wafer pair is heated gradually to 300 $^\circ\text{C}$ in an oven in an N_2 ambient. First, the oven temperature is ramped to 200 $^\circ\text{C}$ linearly from room temperature over a period of one hour. The sample is then held at 200 $^\circ\text{C}$ for one hour. The temperature is then increased by 10 $^\circ\text{C}$ every hour until a final temperature of 250 $^\circ\text{C}$ is reached, where the sample is held at 250 $^\circ\text{C}$ for one hour [14]. During the ramping process, the BCB is fully cured, strengthening the bond. Concurrently, micro-bubbles are formed in the ion-damaged layer, leading to exfoliation of the implanted layer [14]. Finally the wafer pair is heated to 300 $^\circ\text{C}$ over a period of 2 hours and held for one hour before being gradually cooled down to room temperature over a period of 5 hours. As a result, 1.1 μm thick ion-sliced LiNbO_3 is exfoliated from the implanted wafer and transferred to the handle wafer, as shown in Fig. 8(d).

Figure 9(a) shows the transferred LiNbO_3 thin film on the handle wafer. The cross sectional area of the thin film is approximately 0.85 cm by 1.2 cm. A thin film stack of ion-sliced LiNbO_3 , PECVD SiO_2 , and BCB is formed on the surface of the handle wafer, as shown in Fig. 9(b). The root mean square (rms) surface roughness of the transferred thin film is 39 nm, measured with atomic force microscopy. The surface roughness can be reduced to sub-nanometer level by chemical mechanical polishing [15].

The areal shape of the ion-sliced LiNbO_3 is defined by a Cr mask patterned by electron beam lithography (EBL) and plasma etching. A 320 nm thick Cr layer is first deposited on the surface. The sample is then deposited with 300 nm PECVD SiO_2 and coated with 660 nm polymethyl methacrylate (PMMA) resist. The PMMA resist is patterned by EBL and serves as a mask to etch the PECVD SiO_2 layer by inductively coupled plasma reactive ion etching (ICP-RIE) using CHF_3 chemistry. Here, the patterns are in rectangular shapes with edge sizes in the range of hundreds of micrometers. The spacing between each rectangular pattern is 5 μm . After PMMA resist removal, the Cr mask is formed using the PECVD SiO_2 mask by ICP-RIE using Cl_2 and O_2 chemistry, as shown in Fig. 10(a). The ion-sliced LiNbO_3 is then etched through to the BCB using the Cr mask by ICP-RIE using Ar and CHF_3 chemistry. The etching rate of LiNbO_3 is 10 nm/min and the etching selectivity to the Cr mask is 5:1. Five micron wide trenches are formed between each ion-sliced LiNbO_3 rectangular pattern.

After dry etching, the Cr mask is removed with CR-7S chromium etchant, as shown in Fig. 10(b). The sample is then etched in 5% hydrofluoric (HF) acid to undercut the PECVD SiO₂ layer underneath the ion-sliced LiNbO₃ from the etched trenches between patterns, as shown in Fig. 10(c). The horizontal undercut etching rate is approximately 5 $\mu\text{m}/\text{min}$. Figure 11(a) shows the undercut after etching for 4 minutes. Before the ion-sliced LiNbO₃ is fully released by etching, the LiNbO₃ sample is flipped to an unpolished silicon substrate and the etching is resumed with both substrates in the etchant. After etching for 12 min, the ion-sliced LiNbO₃ patterns break away from the SiO₂ pillar. The samples are then rinsed in DI water and dried on a hotplate at 80 $^{\circ}\text{C}$, completing the transfer of the LiNbO₃ films to the unpolished silicon substrate, as illustrated in Fig. 10(d). Figure 11(b) shows patterned ion-sliced LiNbO₃ on the silicon surface with edge lengths of 100 $\mu\text{m} \times 150 \mu\text{m}$ and 100 $\mu\text{m} \times 450 \mu\text{m}$. The maximum pattern size achieved is 100 $\mu\text{m} \times 2 \text{ mm}$. The z-axis of the crystal is along the short edges of the patterns. One corner of the patterns is etched so that the crystal axes can be identified. Rapid thermal annealing (RTA) is then performed at 1000 $^{\circ}\text{C}$ for 30 s to repair the crystal lattice and restore the electro-optical properties of the ion-sliced LiNbO₃ [15].

Device fabrication proceeds as illustrated in Fig. 12. The silicon waveguides are patterned from hydrogen silsesquioxane (HSQ) resist using EBL and ICP-RIE [16]. The sample is coated with BCB and then baked in a N₂ ambient to planarize the surface. Next, the sample is heated to partially cure the BCB. Partial curing helps prevent BCB reflow that may occur after bonding [17]. The BCB is then etched back using ICP-RIE with O₂ and CF₄ chemistry. LiNbO₃ samples prepared on a silicon substrate are transferred to the silicon racetrack using a glass micro-vacuum tip on a probe station. The micro-vacuum tip has a hose diameter of 25 μm and is connected to a vacuum source by plastic tubing. The z-axis of the LiNbO₃ along the short edge of the pattern is aligned to the bus waveguide. The sample is baked to cure the BCB and complete the bonding.

After bonding, the sample is capped with PECVD SiO₂. An access hole is formed by removing the SiO₂ film over the racetrack resonator using ICP-RIE. Metal electrodes are patterned in the access hole with a two-step lithography process to accurately control the narrow electrode gap. The signal electrode is first formed. Then, the ground electrode is aligned to the signal electrode in the second lithography step. An electrode gap is formed with an alignment error smaller than 50 nm. Finally, cantilever couplers are patterned for fiber-to-chip optical coupling [18]. Figure 13 shows top-view optical micrographs of a fabricated device after bonding and electrode patterning.

C. DEMONSTRATION

Demonstration vehicles in the form of gigahertz speed RF electro-optical modulators were developed. Optical transmission measurements were performed to characterize the electrical tuning of optical resonances. Optical light from a tunable infrared continuous-wave laser source was coupled through the input and output fiber-to-chip cantilever couplers of the modulator. DC voltage is applied to the top electrode of the modulator while the bottom electrode is grounded. Figure 14 shows the measured optical mode spectrum as a function of the applied DC voltage. The resonance wavelength redshifts with increasingly positive voltage. The total optical insertion loss for this device is 4.3 dB. The insertion loss is from 3 dB of fiber-to-waveguide coupling loss and 1.3 dB of waveguide transmission loss. The decrease of the optical transmission minimum with voltage is attributed to Fabry-Pérot fringes present due to fiber-to-chip coupling. The resonance shift is 66 pm for a change in DC bias from -10 V to 10 V, indicating 3.3 pm/V tuning, which is equivalent to a V_πL of 9.1 V-cm. The measured quality factor is 14,000, the full-width half-maximum is 13.7 GHz, and the group index is 4.0. At 1551.856 nm, the optical transmission intensity varies by 5.2 dB with a -5 V to 5 V voltage swing, as indicated by the dashed arrow in Fig. 14.

The RF scattering parameter, S₁₁, is measured with a 20 GHz vector network analyzer (VNA) operating in a 50 Ω system. Figure 15(a) shows the measured S₁₁ magnitude and phase data. The magnitude of S₁₁ drops sharply to -2 dB from 40 MHz to 2 GHz, and then gradually rolls off to -4.5 dB at 20 GHz. An RC circuit model extracted from

the measured S_{11} is shown in Fig. 15(b) [19]. Parameter R_C denotes the resistance of the metal electrodes. Parameter C_P represents the parasitic capacitance between the metal electrodes through the top dielectric materials and the air. Parameters C_J and R_S model the electrical path through the silicon transparent electrode and the LiNbO_3 layer. Parameters C_{OX} and R_{Si} model the electrical path through the buried oxide and the silicon substrate. The value of C_J is in good agreement with finite element method simulations. The relatively high value of R_S indicates a lower than expected doping concentration in the waveguide and a higher than expected contact resistance [20]. The relatively large C_P value is mainly attributed to the parasitic capacitance of the electric pads. The sharp drop at the lower frequency band is attributed to the RF coupling through the substrate.

The small-signal electrical-to-optical modulation response is shown in Fig. 16. The modulated optical signal is detected with a photodetector with a 3 dB bandwidth of 12 GHz. Also shown in Fig. 16 is the frequency response of the voltage across C_J in the circuit model shown in Fig. 15(b). The measured 3 dB optical response bandwidth of the modulator is approximately 5 GHz. While the general trend of the optical responses match the circuit model, the optical response contains additional dips and peaks across the entire frequency band.

The dips and peaks on the optical modulation response are a result of acousto-optic resonances [21,22,23]. The electric fields between the electrodes excite acoustic waves in the 1 μm thick LiNbO_3 producing resonances in the gigahertz frequency range. Multiple resonance peaks apparent in the S_{11} measurements at 1.7 GHz and corresponding harmonics indicate the conversion of the electrical energy to acoustic energy at the acoustic resonances. Consequently, refractive index changes occur in the LiNbO_3 through the elasto-optic effect. The acoustic resonances can be suppressed by roughening the surface of the piezoelectric material to increase the scattering loss of the acoustic wave [24,25]. The surface roughness can be produced by dry or wet etching. Sufficiently thick LiNbO_3 avoids optical mode interaction with the rough surface.

A schematic for high-speed digital modulation characterization is shown in Fig. 17 [19]. A pulse pattern generator (PPG) outputs a $2^{31}-1$ pseudo-random-bit-stream data stream (PRBS31) with a voltage swing from -1 V to 1V. The peak-to-peak amplitude of the signal is amplified to 5 V (-2.5V to 2.5 V) with a modulator driver amplifier. The output light from the modulator is passed through a fiber amplifier and an optical passband filter with 0.5 nm bandwidth to amplify the signal and suppress the amplified spontaneous emission noise. The amplified optical signal is attenuated and connected to a 30 GHz optical module on a digital communication analyzer (DCA) synchronized to the clock of the PPG for generating optical eye diagrams. The optical bias wavelength is tuned to maximize the extinction ratio (ER).

The left column of Fig. 18 shows measured optical eye diagrams at 1 Gb/s, 4.5 Gb/s, 5 Gb/s, and 9 Gb/s, with extinction ratios of 4.7 dB, 4.5 dB, 4 dB and 3 dB, respectively. The right column of Fig. 18 shows simulated eye diagrams at the corresponding bit rates with ideal PRBS driving signals. The extinction ratio and shape of the simulated optical eyes agree well with the measurement results. In particular, the amplitude ringing for the 1 Gb/s eye and the partial eye closing on the left part of the 5 Gb/s eye closely match the simulation.

The total energy consumption of the modulator is estimated to be 4.4 pJ/bit at 9 Gb/s with a 10 V swing. The energy per bit encompasses 0.4 pJ/bit from C_J , 1.8 pJ/bit from C_P , and 2.2 pJ/bit from C_{OX} . The energy consumption on C_J is only 9% of the total energy consumption. The majority of the energy consumption is attributed to charging and discharging of the large area electrical pads for test and measurement. Energy consumption can be reduced by optimizing device capacitances. Steady state DC power consumption for tuning of optical resonance frequencies is ideally zero in the capacitive device.

FIGURES

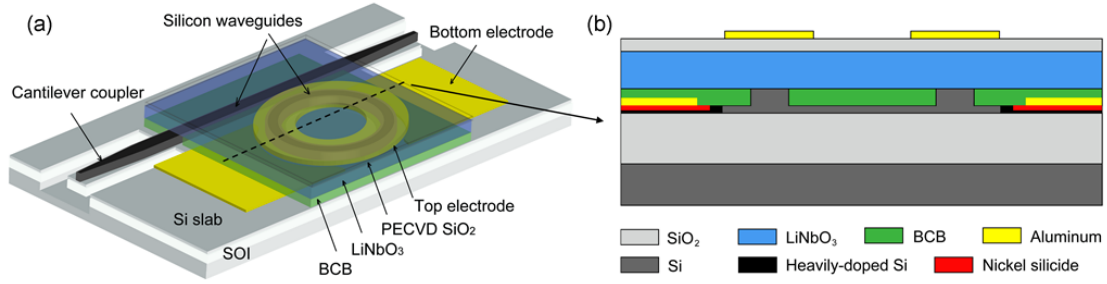


Fig. 1. (a) Schematic of a tunable hybrid silicon and LiNbO₃ microring resonator with integrated electrodes. (b) Schematic of the cross-section of the device structure along the dashed line shown in (a). The design is intended for transverse magnetic (TM) optical modes.

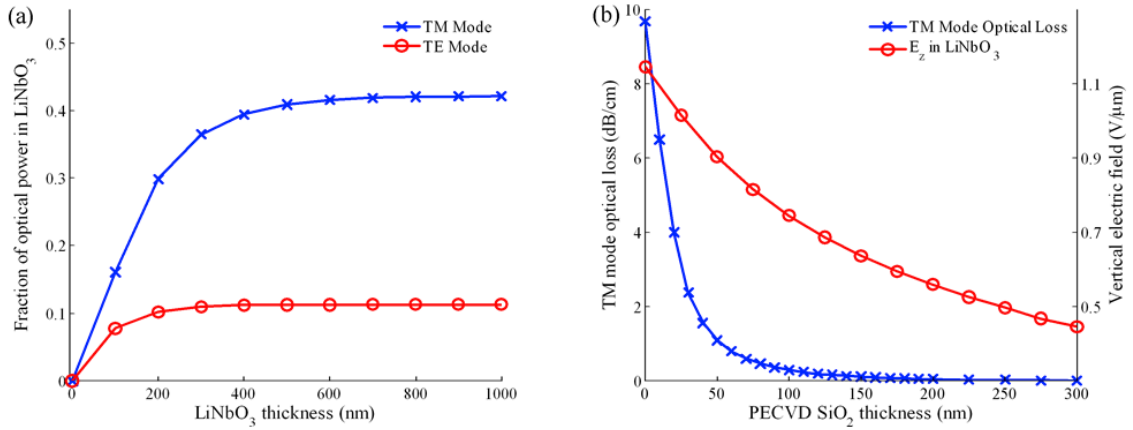


Fig. 2. (a) Beam Propagation Method (BPM) calculations of the optical mode power in LiNbO₃ versus the thickness of LiNbO₃ for the transverse magnetic (TM) mode and the transverse electric (TE) mode in the hybrid Si/LiNbO₃ structure. (b) Calculations of the optical loss (blue) induced by the top aluminum electrode and the voltage induced vertical electric field in LiNbO₃ (red) versus the PECVD silicon dioxide thickness. The LiNbO₃ thin film thickness is set to be 800 nm and the applied voltage is 1 V.

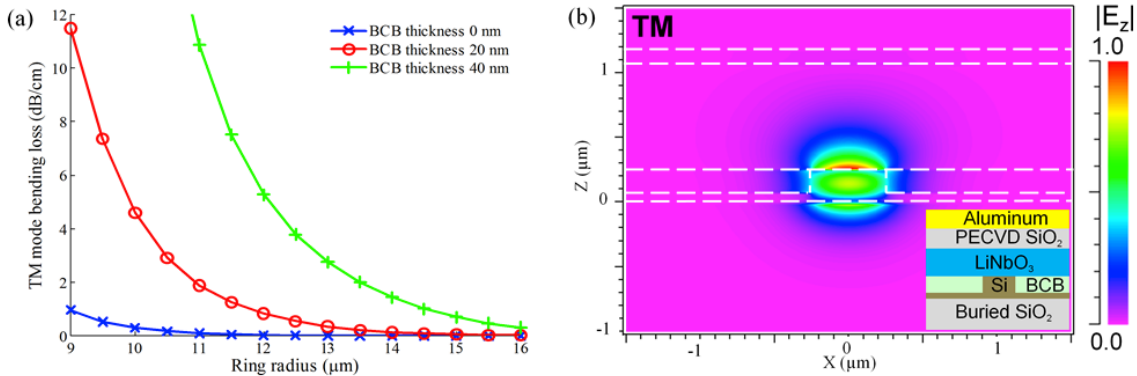


Fig. 3. (a) Calculated TM mode optical bending loss versus the ring radius for BCB thickness of 0 nm, 20 nm, and 40 nm between the top of the silicon core and the bottom of the LiNbO₃ thin film. (b) Calculated optical electric field distribution of the hybrid silicon and LiNbO₃ structure for the fundamental TM mode at 1550 nm wavelength (E_z component).

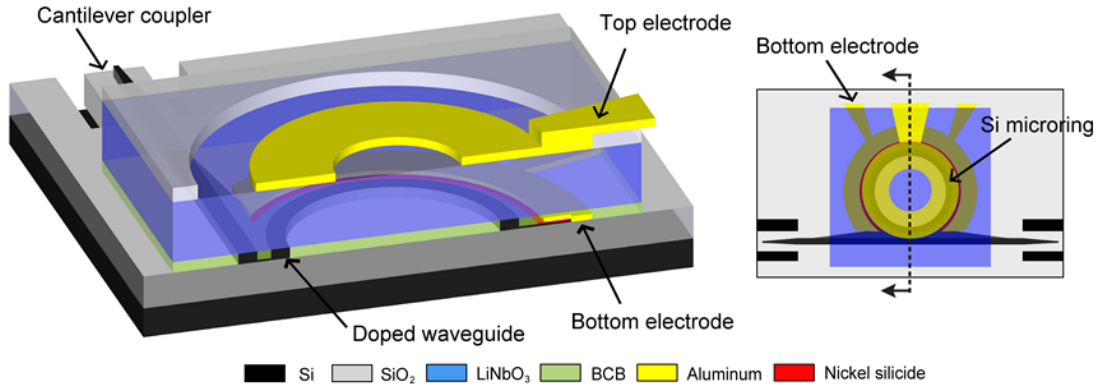


Fig. 4. Schematic of hybrid silicon and lithium niobate ring resonator designed for high electrical frequency operation and in the transverse electric (TE) optical mode.

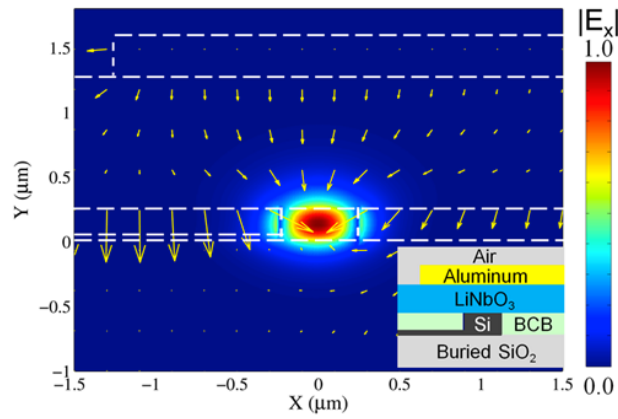


Fig. 5. Calculated optical TE mode distribution at 1550 nm wavelength (E_x component) and DC voltage induced electric field vectors.

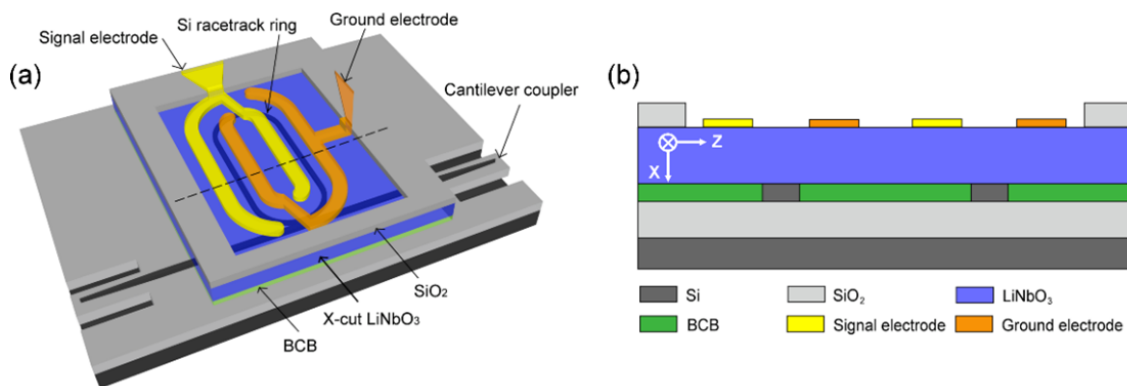


Fig. 6. (a) Schematic of hybrid Si/LiNbO₃ ring modulator. For clarity, the PECVD SiO₂ top-cladding layer and electrical contact pads are not shown. (b) Schematic of cross-section of device along dashed line in (a).

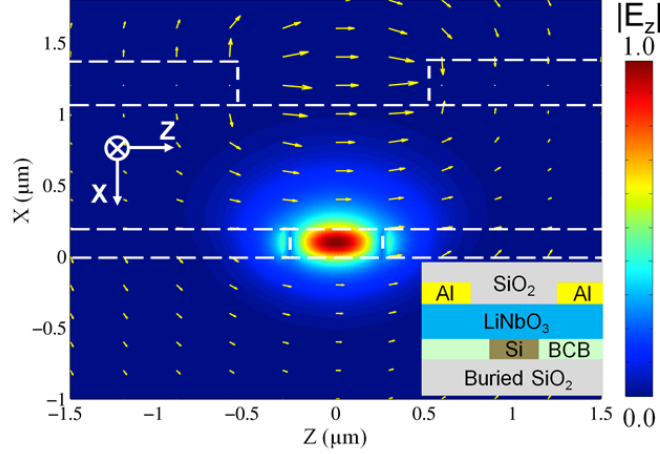


Fig. 7 Calculated optical TE mode distribution at 1550 nm wavelength and electric field vectors from applied DC voltage.

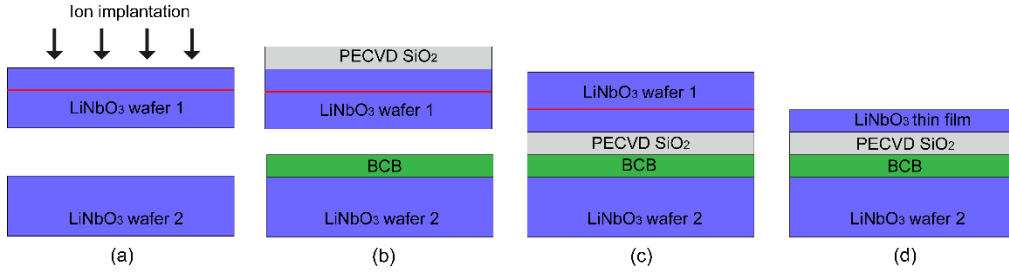


Fig. 8. Ion-sliced LiNbO₃ exfoliation: (a) He⁺ ion implantation on wafer 1, (b) PECVD SiO₂ deposition on wafer 1 and BCB spin-coating on wafer 2, (c) wafer bonding and annealing, (d) exfoliation of ion-sliced LiNbO₃.

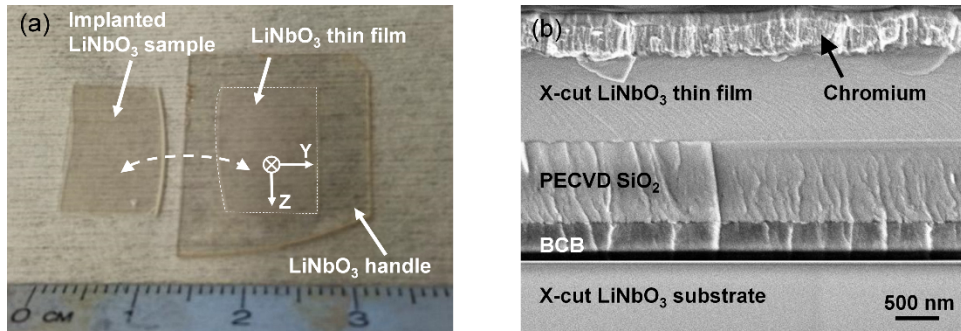


Fig. 9. (a) X-cut ion-sliced LiNbO₃ bonded to a LiNbO₃ handle substrate. The wafers are diced into rectangular samples for identification and alignment of the crystal z-axes. (b) Scanning electron micrograph (SEM) of the cross-section of the thin film stack. The dark line in the BCB layer is due to charging during the scanning electron microscopy.

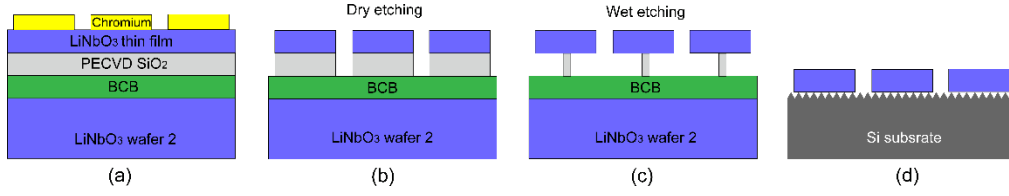


Fig. 10. Patterned ion-sliced LiNbO₃ fabrication flow: (a) patterning Cr mask, (b) dry etching of LiNbO₃, (c) wet etching of PECVD SiO₂, (d) Transferring LiNbO₃ to an unpolished silicon substrate.

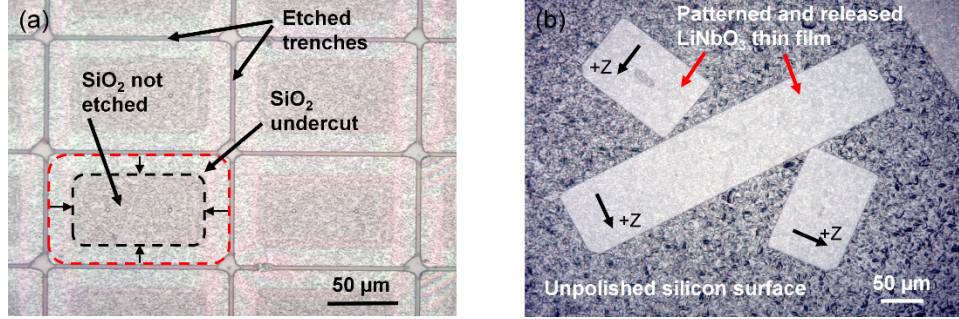


Fig. 11. (a) HF acid etching of the patterned x-cut ion-sliced LiNbO₃; (b) Released ion-sliced LiNbO₃ transferred to the unpolished surface of a silicon substrate.

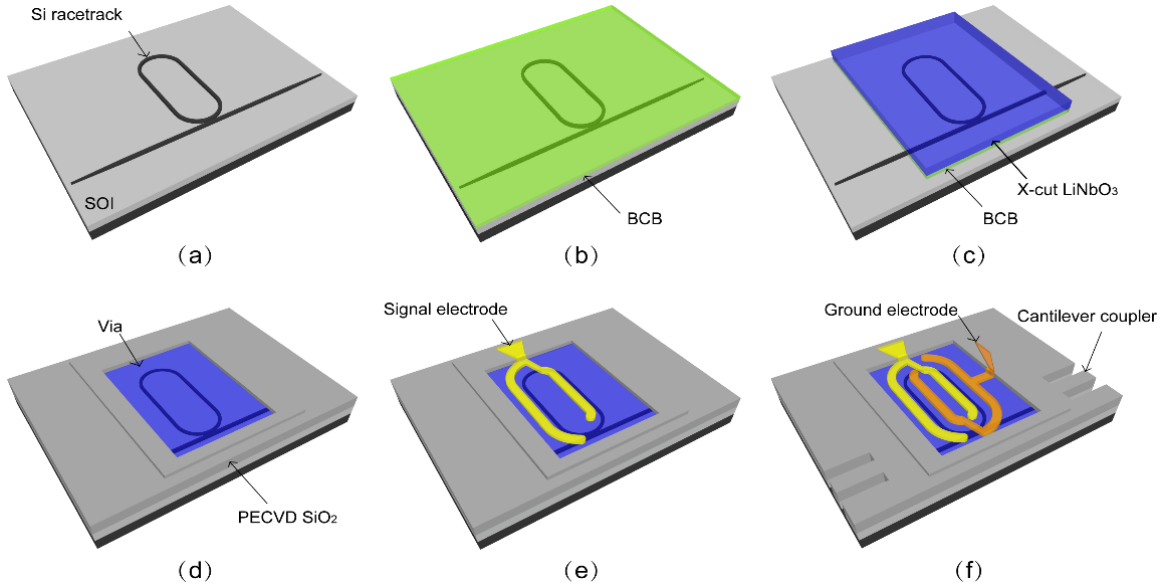


Fig. 12. Fabrication process of Si/LiNbO₃ racetrack resonator: (a) Silicon strip patterned on silicon-on-insulator wafer using EBL and plasma etching; (b) spin-coat, partial curing, and etch back of BCB; (c) bonding of LiNbO₃ and plasma etch of BCB; (d) deposition of PECVD SiO₂ and removal of SiO₂ above the resonator; (e) patterning of signal electrode; (f) patterning of ground electrode and cantilever couplers.

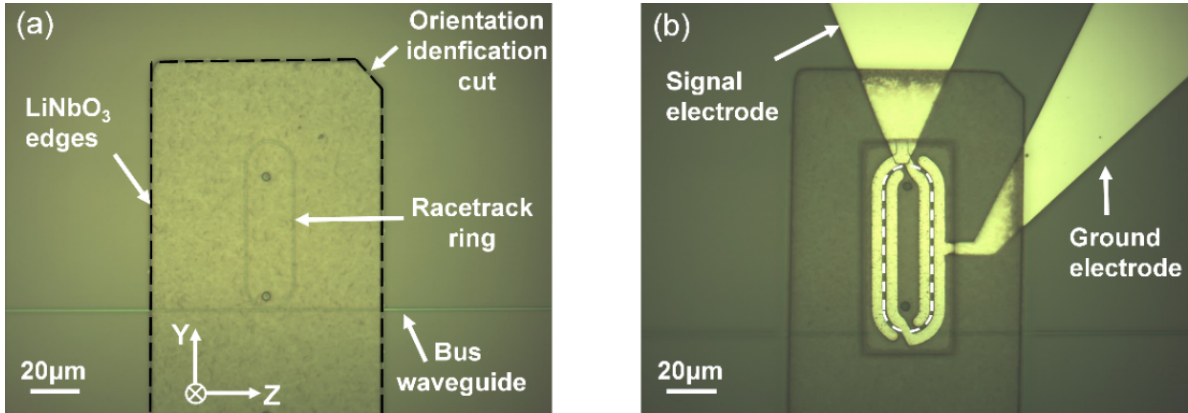


Fig. 13. Top-view optical micrograph of fabricated Si/LiNbO₃ racetrack resonator. (a) Image of device after bonding of the LiNbO₃; (b) Image of device after patterning of the electrodes.

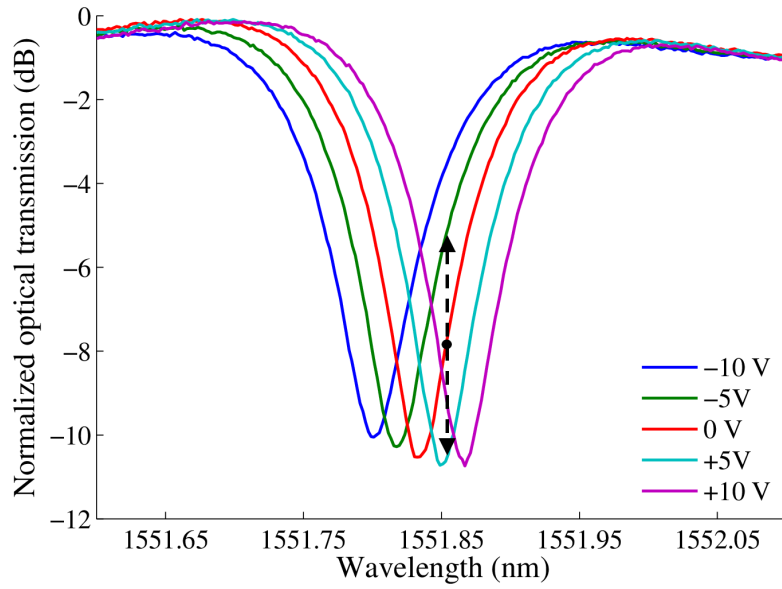


Fig. 14. Measured optical transmission of a single resonance as a function of applied voltage.

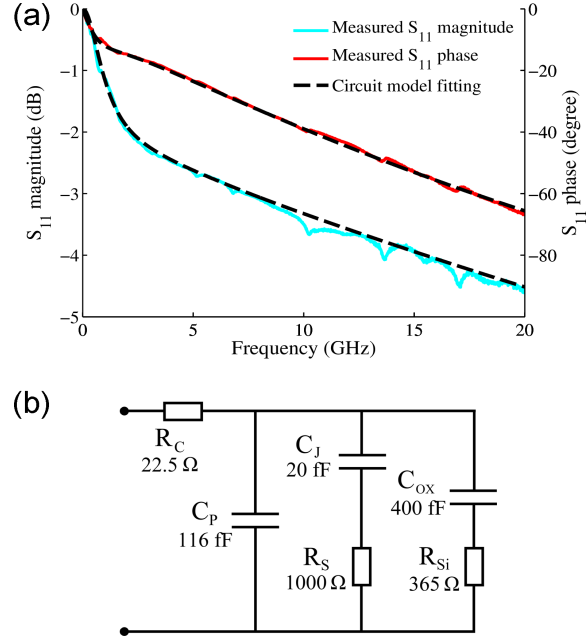


Fig. 15. (a) RF S_{11} scattering parameter; (b) RC circuit model of the modulator.

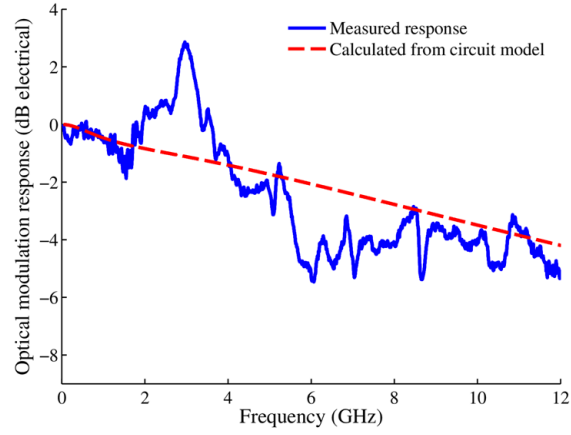


Fig. 16. Electrical-to-optical modulation response.

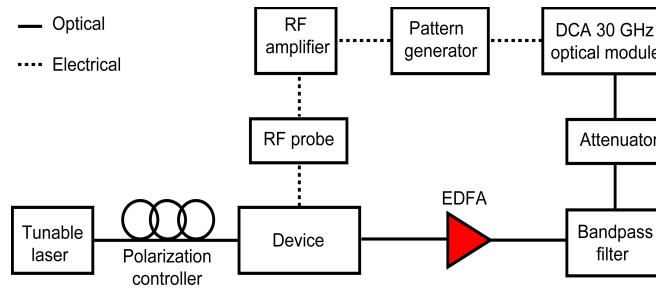


Fig. 17. Measurement setup for digital characterization

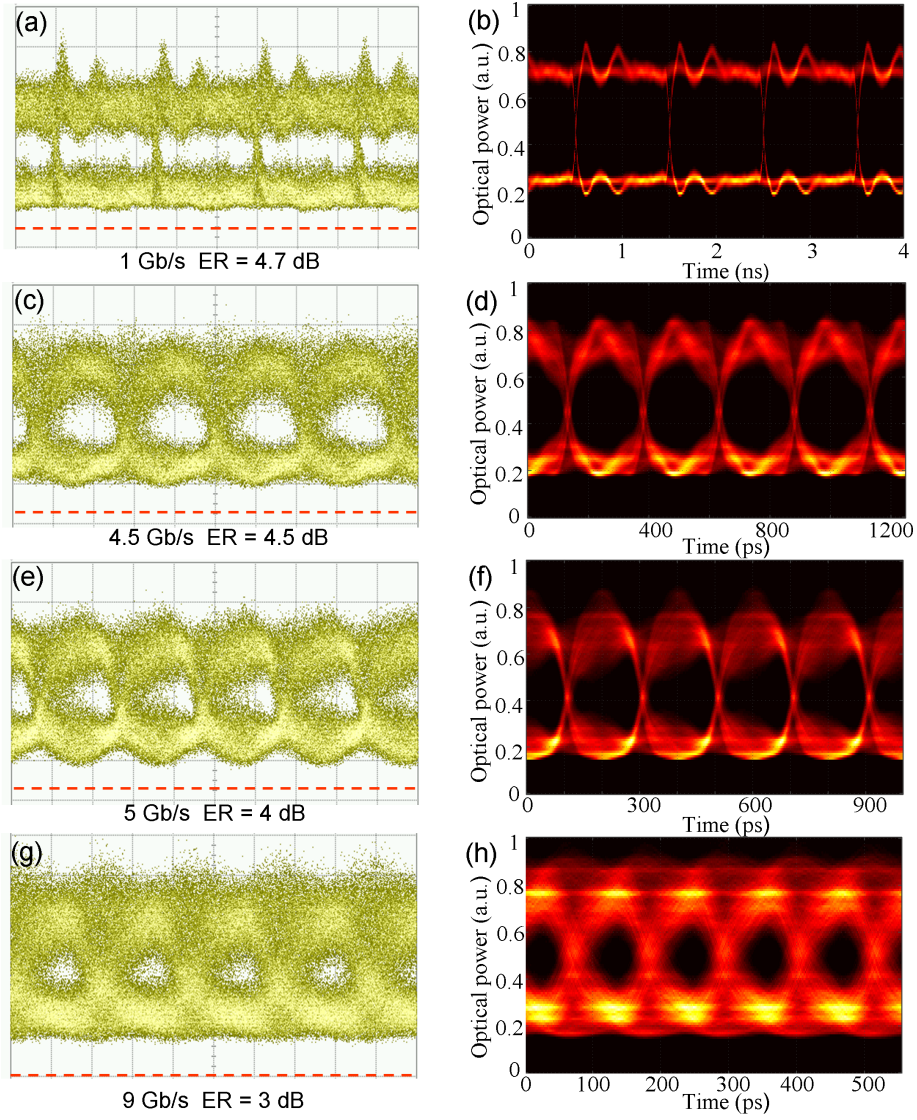


Fig. 18. Measured (left column) and simulated (right column) optical eye: (a) and (b) 1 Gb/s, (c) and (d) 4.5 Gb/s, (e) and (f) 5 Gb/s, (g) and (h), 9 Gb/s. The red dashed line in the measurement indicates the reference level for zero optical input. The vertical scale is 500 μ W per division.

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