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24 - 26 August 2016

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The Group IV Photonics Conference (GFP 2016), now in its 13th year, delivers insights on current and future innovations in Group IV element-based photonic materials and devices, including silicon photonics, as well as other integration and fabrication technologies. Scheduled as a single-track conference, GFP 2016 facilitates personal interaction between colleagues, including oral and poster sessions of contributed and invited papers, as well as a plenary session with overviews of important Group IV element photonics topics.

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Group IV Photonics 2016 Program at-a-Glance

TUESDAY, 23 AUGUST	WEDNESDAY, 24 AUGUST	THURSDAY, 25 AUGUST	FRIDAY, 26 AUGUST
All Sessions will be in the Suncuba Ballroom	**WA:** Welcome Remarks/Plenary I/Systems & Subsystems 8:00am-10:00am	**ThA:** Plenary II/ Passives & Couplers I 8:15am-10:00am	**FA:** Lasers & Light Sources 8:00am-10:00am
	EXHIBITS/COFFEE BREAK 10:00am-10:30am		
9:00am-1:00pm Masterclass: Designing Silicon Photonic Wavelength Filters **Sponsored by: Luceda Photonics and Ghent University**	**WB:** Modulators, Switches & Thermal Control 10:30am-12:00pm	**ThB:** Hybrid Photonics 10:30am-12:00pm	**FB:** Passives & Couplers III 10:30am-12:00pm Best Papers & Best Posters Award Ceremony 12:00pm-12:20pm
	LUNCH BREAK (ON OWN) 12:00pm-1:30pm		LUNCH BREAK (ON OWN) 12:20pm-1:30pm
2:00pm-6:00pm Silicon Photonics Workshop **Sponsored by: Synopsys & PhoeniX Software** Followed by a Coffee Break	**WC:** Sources & Detectors 1:30pm-3:30pm	**ThC:** Photonic Circuits 1:30pm-3:30pm	**FC:** Integration Platforms 1:30pm-3:30pm
	EXHIBITS/COFFEE BREAK 3:30pm-4:00pm		
	WD: Germanium Photonics 4:00pm-5:30pm	**ThD:** Passives & Couplers II 4:00pm-5:30pm	**FD:** Transceivers 4:00pm-5:30pm
	Welcome Reception 5:30pm-7:30pm **Havana Nights** **Sponsored by: Intel Corporation**	**ThP:** Poster Session 5:30pm-7:00pm **Havana Nights** **Sponsored by Luceda Photonics**	**Post-Deadline Session** 5:30pm-6:30pm

WD5 5:00 PM-5:15 PM

Direct Band Gap Germanium in High Q-Factor Cavities, M. El Kurdi, A. Elbaz, M. Prost, A. Ghrib, R. Ossikovski, G. Picardi and S. Sauvage, *IEF CNRS/Université Paris-Sud, Orsay, France*, X. Checoury and G. Beaudouin, *LPICM, CNRS/Ecole Polytechnique, Palaiseau, France*, I. Sagnes and F. Boeuf, *LPN,UPR20 CNRS, Marcoussis, France*, P. Boucaud, *STMicroelectronics, Crolles, France*

Direct band gap germanium microdisks are obtained by applying high tensile strain using external stressor layers. We performed temperature dependent photoluminescence analysis to quantify that the indirect-to-direct band gap transition occurs at 1.67% of biaxial strain and study the emission on high Q-factor strained cavities.

WD6 5:15 PM-5:30 PM

Highly Strained Direct Bandgap Germanium Cavities for a Monolithic Laser on Si, T. Zabel, E. Marin, R. Geiger and C. Bonzon, *Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, Villigen*, S. Tardif, *Institute for Quantum Electronics, ETH Zürich, Zürich*, K. Guilloy, A. Gassenq, J. Escalante, Y. Niquet, I. Duchemin and J. Rothman, *University Grenoble Alpes, CEA INAC, Grenoble*, N. Pauc, F. Rieutord, V. Reboud, V. Calvo, J. Hartmann, J. Widiez, A. Tchelnokov and J. Faist, *CEA-LETI Minatec Campus, Grenoble*, H. Sigg, *Institute for Quantum Electronics, ETH Zürich, Zürich*

Cavity enhanced photoluminescence at a wavelength as long as 5 µm is obtained in uniaxial tensile strained GeOI micro-bridges. We show, using temperature dependent photoluminescence spectroscopy, a crossover to fundamental direct bandgap and reveal from a mode analysis the free carrier induced loss increase.

5:30 PM-7:00 PM Welcome Reception: Havana Nights- Sponsored by Intel Corporation

Thursday, 25 August 2016

8:15 AM-10:00 AM
Session ThA: Plenary II/Passives & Couplers
Session Chair: Zhiping (James) Zhou, Peking University, China & Lin Yang, IOSCAS, China

8:15 AM-9:00 AM Plenary II- Introduced by Lin Yang, IOSCAS, China

9:00 AM-10:00 AM Contributed talks - Chaired by Zhiping (James) Zhou, Peking University, China

ThA1 8:15 AM-9:00 AM (Plenary)

Silicon Photonics: A University Perspective, G. Reed, *Southampton University, United Kingdom*

ThA2 9:00 AM-9:15 AM

SiGe-on-SOI Mach-Zehnder Modulators Enabling Large Mode Size Edge Coupling, X. Sun, F. Li, Z. Shao, W. Guo, Y. Huang, F. Liu and L. Jia, *LaXense, Inc., Walnut, CA, California*, N. Feng and J. Hu, *MIT, Cambridge, Massachusetts, USA*

A SiGe-on-SOI carrier-depletion Mach-Zehnder modulator is presented. Compared with Si modulators, it eliminates advanced lithography by enabling a dual-waveguide design using small SiGe waveguides for modulators and large Si waveguides for edge coupling. DC and high speed test results are included.

ThA3 9:15 AM-9:30 AM

Comparison and Analysis on Single-Layer Si Fiber-to-Chip Edge Couplers with Different Taper Tips, J. Wang, Y. Xuan and M. Qi, *Huawei Technologies Co, Ltd, Shenzhen,* L. Liu and N. Liu, *Purdue University, West Lafayette, Indiana, USA*

We presented a comparison and analysis on single-layer silicon fiber-to-chip edge couplers with different taper tips. The double-tip edge coupler exhibits a lower coupling loss, larger bandwidth and better fabrication tolerance. In addition, the short edge couplers with 40 μm length have the best performances.

ThA4 9:30 AM-9:45 AM

Optimizing Undercut in Highly-Stressed $Ge_{0.934}Sn_{0.066}$ Microdisk Resonators, C. Fenrich, X. Chen, Y. Huang, H. Chung and Y. Huo, *Stanford University, Stanford, California,* USA, T. Kamins and J. Harris, *Applied Materials Inc., Sunnyvale, California, USA*

Undercut width provides an additional degree of tunability in bandstructure engineering for highly-stressed $Ge_{0.934}Sn_{0.066}$ microdisk resonators for on-chip light sources. An optimal undercut design balances considerations such as mode confinement and mode overlap with high strain (and direct bandgap) gain regions of the resonator.

ThA5 9:45 AM-10:00 AM

Compact Low-Loss Adiabatic Bends in Silicon Shallow-Etched Waveguides, X. Tu, M. Li, J. Jiang and D. Goodwill, *All-Optics Laboratory, Huawei Technologies Co. Ltd, Shenzhen,* P. Dumais, E. Bernier, H. Fu and D. Geng, *Huawei Technologies Canada Co. Ltd., Ottawa, Canada*

We report an adiabatic bend based on silicon shallow-etched waveguide using a sine-circle-sine design. The loss per 180° turn is 0.05 dB for 5 mm bend and 0.008 dB 10 mm bend for TE polarization, which are significantly lower than that of a circular bend.

10:00 AM-10:30 AM Coffee Break/Exhibits: Huangpu Room and Meeting Room 2 & 3

10:30 AM-12:00 PM
Session ThB: Hybrid Photonics
Session Chair: Dries Van Thourhout, Ghent University, Belgium

ThB1 10:30 AM-11:00 AM (Invited)

Hybrid III-V/Silicon Photonic Integrated Circuits for Optical Communication Applications, G. Duan, *III-V Lab, France*

ThB2 11:00 AM-11:30 AM (Invited)

Integrated Hyperuniform Polarizers and Nanophotonic Mode Demultiplexers, H. Tsang, W. Zhou and L. Liu, *The Chinese University Of Hong Kong, Hong Kong*

We present results on an integrated polarizer formed by the polarization dependent photonic bandgap produced by a hyperuniform disordered wall network. We also describe the use of an inverse numerical design approach to design a mode multiplexer/demultiplexer for mode division multiplexed optical interconnects.

ThB3 11:30 AM-11:45 AM

Silicon Integrated Nonreciprocal Photonic Devices Using Monolithically Integrated Magnetic Oxides, L. Bi, Y. Zhang, K. Shui, J. Qin, X. Liang, L. Nie and L. Deng, *University of Electronic Science and Technology of China, Chengdu, China*

We report our recent progress on monolithic integration of magneto-optical oxides and devices on silicon, including monolithic integration of $Ce_{1.5}Y_{1.5}Fe_5O_{12}$ films on silicon with large Faraday rotation at 1550 nm, and a broadband optical isolator design using MMI showing compact device footprint of 310.42 um.

ThB4 11:45 AM-12:00 PM

Towards High-Speed Electro-Optical Performance in a Hybrid BaTiO3/Si Mach-Zehnder Modulator, P.Castera, A. Rosa, A. Gutierrez and P. Sanchis, Nanophotonics Technology Center, Universitat Politècnica de València, Valencia, D. Tulli, DAS Photonics, Valencia, S. Cueff, R. Orobtchouk, P. Romeo and G. Saint-Girons, Lyon Institute of Nanotechnology, Lyon

A Mach-Zehnder modulator based on a hybrid BaTiO3/silicon optical waveguide has been designed to achieve a high modulation bandwidth with a simulated VπL below 1V·cm and RF impedance matching. The device has been fabricated and characterized in the DC regime.

12:00 PM-1:30 PM Lunch (On Own)

1:30 PM-3:30 PM
Session ThC: Photonic Circuits
Session Chair: Koji Yamada, National Institute of Advanced Industrial Science and Technology, Japan

ThC1 1:30 PM-2:00 PM (Invited)

Silicon-Organic Hybrid (SOH) Devices and Their Use in Comb-Based Communication Systems, C. Koos, W. Freude, S. Wolf, H. Zwickel, M. Lauermann, C. Weimann, W. Hartmann, J. Kemal, P. Marin, P. Trocha and J. Pfeifle, *Karlsruhe Institute of Technology (KIT),* L. Dalton and D. Elder, *University of Washington*, T. Kippenberg, T. Herr and V. Brasch, *Ecole Polytechnique Fédérale de Lausanne (EPFL)*, L. Barry and R. Watts, *The Rince Institute, School of Electronic Engineering*, A. Ramdane, *Laboratoire de Photonique et Nanostructures*, F. Lelarge and N. Chimot, *III-V Labs*, A. Martinez and V. Panapakkam, *Laboratoire de Photonique et Nanostructures*

Advanced wavelength-division multiplex-ing (WDM) requires both efficient multi-wavelength light sources to generate optical carriers and highly scalable photonic-electronic interfaces to encode data on these carriers. In this paper, we give an overview on our recent progress regarding silicon-organic hy-brid (SOH) integration and comb-based WDM transmission.

ThC2 2:00 PM-2:15 PM

Microring Modulator Matrix Integrated with Mode Multiplexer and De-Multiplexer for on-Chip Optical Interconnect, H. Jia, C. Yuan, L. Zheng, J. Ding, L. Zhang, X. Fu and L. Yang, *Institute of Semiconductors, CAS, Beijing, China*

We report a 4´4 microring modulator matrix integrated with mode multiplexer and demultiplexer based on asymmetrical directional couplers (ADCs) for on-chip optical interconnect. Data transmission with the capacity of 512 Gbps is demonstrated by adopting 4 wavelengths and 4 modes multiplexing.

ThC3 2:15 PM-2:30 PM

Vertical Trident Coupler for 3D Optical Interconnection, K. Itoh, Y. Kuno, Y. Hayashi, J. Suzuki, T. Amemiya, N. Nishiyama and S. Arai, *Tokyo Institute of Technology, Tokyo*

A vertical trident coupler for 3D optical circuit was demonstrated. The trident structure can manage both easiness of fabrication and high coupling even with relatively thick interlayer distances. In experiment, this trident coupler realized low coupling loss (coupling efficiency) of 0.58dB (87%) at 1550 nm.

ThC4 2:30 PM-2:45 PM

Towards Flexible, Scalable and Low Loss Non-Reciprocal System in Silicon Photonics, Y. Yang, *University of Toronto, Toronto,Ontario*, Canada, C. Galland, *Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne*, Y. Liu, T. Baehr-Jones and M. Hochberg, *Coriant Advanced Technology Group, New York, USA*

A silicon photonic non-reciprocal isolator/circulator system with time-dependent permittivity tensor is demonstrated. In addition to being broadband and low loss, the architecture is scalable to achieve high extinction ratio with reconfigurable isolation path direction.

ThC5 2:45 PM-3:00 PM

Stable Unidirectional Emission Hybrid Deformed-Ring Microlaser Coupled to a Silicon Waveguide, S. S. Sui and Y. Z. Huang, State Key Lab on Integrated Optoelectronics, *Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China*

Mode characteristics are investigated to realize stable unidirectional emission for a locally deformed-ring resonator. Using DVS-BCB bonding technique, hybrid silicon deformed-ring microlasers are fabricated coupled to a silicon waveguide, and threshold current of 7 mA and unidirectional power output from CCW direction are obtained.

ThC6 3:00 PM-3:15 PM

Parametric Characterization of Self-Heating in Si Micro-Ring Modulators, M. Shin, W-Y. Choi and B. Yu, *Department of Electrical and Electronic Engineering, Yonsei University, Seoul*, Korea, L. Zimmermann, *IHP, Frankfurt, Germany*

Influence of self-heating on Si Micro-Ring Modulator (MRM) characteristics is modeled by adding a newly-introduced self-heating coefficient to the existing coupled-mode model. With this, Si MRM transmission spectra and modulation frequency responses are accurately modeled for different input optical powers producing different amounts of self-heating.

ThC7 3:15 PM-3:30 PM

Strictly Non-blocking 4×4 Silicon Electro-optic Switch Based on a Double Layer Network Architecture, Z. Guo, L. Lu, S. Zhao, L. Zhou and J. Chen, *State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai, China*

We report a 4×4 silicon switch based on a double layer network architecture by cascading three stages of electrically tunable Mach-Zehnder interferometers (MZIs). Preliminary experiment reveals that the switch has on-chip insertion loss less than 4 dB and crosstalk lower than -30 dB

3:30 PM-4:00 PM Coffee Break/Exhibits: Huangpu Room and Meeting Room 2 & 3

4:00 PM-5:30 PM
Session ThD: Passives and Couplers II
Session Chair: Hon Tsang, The Chinese University of Hong Kong, China

ThD1 4:00 PM-4:30 PM (Invited)

Silicon Photonic Polarization Beamsplitter and Rotator for On-Chip Polarization Control, Z. Lu, M. Ma, H. Yun, Y. Wang, N. Jaeger and L. Chrostowski, *University of British Columbia, Vancouver, British Columbia, Canada*

Polarization beamsplitters (PBSs) and polarization rotators (PRs) are essential components for polarization control in silicon photonic integrated circuits. Here, we review our recent work on both component and circuit designs for polarization control.

ThD2 4:30 PM-4:45 PM

Si Photonic Active Controller for Polarization Independent Coupling, T. Cassese, G. De Angelis, P. Velha, V. Sorianello and M. Preite, *Scuola Superiore Sant'Anna – TeCIP Institute, Pisa,* A. Bianchi and F. Testa, *CNIT – Ericsson Research Pisa, Italy,* G. Contestabile and M. Romagnoli, *CNIT-Laboratory of Networks, Pisa, Italy*

A photonic integrated circuit capable of recombining any incoming state of polarization into a single TE Silicon waveguide was demonstrated, allowing optical communication systems to be transparent to polarization issues.

ThD3 4:45 PM-5:00 PM

Improving the Efficiency of Fibre-Chip Grating Couplers Near 1310 nm, X. Chen, *Optoelectronics Research Centre, Southampton*, D. Thomson, L. Crudgington, A. Khokhar and L. Gao, *ORC, Southampton*, X. Song, Y. Li and G. Reed, *Huawei, Shenzhen*

We present our recent work on fibre-chip grating couplers operating around 1310 nm. For the first time, we demonstrated the combination of dual-etch and apodization design approaches which can offer state of the art performance. Initial tests from fabricated structures show a -2.2dB loss.

ThD4 5:00 PM-5:15 PM

Impact of Scattering Element Shape on Polarisation Dependent Loss in Two Dimensional Grating Couplers, S. Plantier, D. Fowler, K. Hassan and O. Lemonnier, *Univ. Grenoble Alpes, CEA, LETI,*

MINATEC Campus, Grenoble, R. Orobtchouk, *Institut des Nanotechnologies de Lyon (INL), CNRS UMR 5270, Université de Lyon, INSA-Lyon, Villeurbanne, France*

We experimentally demonstrate the impact on polarization dependent loss (PDL) of the scattering element shape in a 2D grating coupler. Using e-beam lithography, we show that PDL may be reduced by more than 1.5dB with respect to gratings using simple circular scattering elements.

ThD5 5:15 PM-5:30 PM

Low-Loss and Low-Crosstalk Si Etched Diffraction Gratings with Multi-Point Iterative Optimization, T. Ye and T. Chu, *Institute of Semiconductors, Chinese Academy of Science, Beijing, China*

Low-insertion loss and low-crosstalk silicon etched diffraction gratings (EDGs) with a multi-point iterative optimization were demonstrated. By using CMOS 180 nm fabrication processing, high performance EDGs with an insertion loss of approximately 1.0–1.5 dB and crosstalk below -30 dB were implemented.

5:30 PM-7:30 PM HAVANA NIGHTS
Session ThP: Poster Session- Sponsored by Luceda Photonics
Session Chair: Koji Yamada, National Institute of Advanced Industrial Science and Technology, Japan

ThP1 5:30 PM

On-Chip Differential Phase Monitoring with Balanced Photodiodes, A. Ribeiro, *Ghent University - IMEC, Photonics Research Group, Ghent*, K. Miura and T. Spuesens, *Ghent University - IMEC, Photonics Research Group, Department of Information Technology, Ghent, Belgium, Ghent*, W. Bogaerts, *Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo, Japan, Tokyo*

We present on-chip differential phase shift monitoring between delay lines of a phased array using integrated balanced photodiodes. We compare the results of the differential measurement to a measurement using an external reference Mach-Zender interferometer.

ThP2 5:30 PM

Ultra-dense Silicon Photonics Optical IO Solution for Optical Chip Scale Package, Q. Zhao, X. Song, M. Quan, Z. Dong, R. Ji, Y. Li, L. Gao, L. Hao, S. Fu and L. Zeng, *Huawei Technologies Co, Ltd, Shenzhen, China*

Optical chip scale package is a key transceiver technology for future communication networks. A novel scheme is proposed with 336 electrical and optical channels integrated on single substrate. A novel ultra-dense optical IO solution for silicon photonics chips is proposed as an important enabling technology.

ThP3 5:30 PM

Complexity in Nonlinear Delayed Feedback Oscillator with Silicon Mach-Zehnder Modulator, L. Zhang, J. Ding and L. Yang, *State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing*, Y. Peng, J. Jia, H. Yang and J. Xiao, *School of Science, Beijing University of Posts and Telecommunications, Beijing, China*

Parametric Characterization of Self-Heating in Si Micro-Ring Modulators

M.-J. Shin(1), B.-M. Yu(1), L. Zimmermann (2) and W.-Y. Choi(1)

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(2) IHP, Im Technologiepark 25, 15236 Frankfurt (Oder), Germany

ABSTRACT

Influence of self-heating on Si Micro-Ring Modulator (MRM) characteristics is modeled by adding a newly-introduced self-heating coefficient to the existing coupled-mode model. With this, Si MRM transmission spectra and modulation frequency responses are accurately modeled for different input optical powers producing different amounts of self-heating.

Depletion-type Si micro-ring modulators (MRMs) can operate at very high modulation frequencies with a very small footprint and, because of these, have a great potential for integration with Si electronics in challenging optical interconnect applications [1], [2]. However, Si MRMs suffer from self-heating caused by free carrier absorption of the input light circulating in the ring waveguide [3]. With self-heating, the effective refractive index of the ring waveguide increases due to temperature rise and the resonance wavelength shifts into the longer wavelength, the amount of which depends on the input optical power. Since Si MRM modulation characteristics greatly depend on the resonance wavelength, the self-heating phenomenon in Si MRMs must be well understood and accurately modeled in order to achieve optimal and reliable Si MRM operation. In this paper, we achieve these by introducing a self-heating coefficient, *R*, to the existing Si MRM model based on the coupled-mode theory.

Fig. 1(a), (b) show the structure and cross-section of a Si MRM device, respectively, used for our investigation. The device was fabricated through Si PIC MPW provided by IHP. It has ring radius of 8um, gap distance of 290nm, and nominal doping concentration of $7\text{x}10^{17}(\text{cm}^{-3})$ for P-region and $5\text{x}10^{18}(\text{cm}^{-3})$ for N-region. Fig. 1(c) shows the measured transmission spectra of the device at five different input optical powers. As the input optical power becomes larger, the resonance wavelength shifts to the longer wavelength and the transmission spectrum becomes asymmetric due to self-heating. The amount of the resonance peak shift can be linearly fitted as shown in the Fig. 1(d) and can be modeled as $\Delta\lambda_{res} = \frac{\lambda_{res}}{n_g} R \Delta I_{in}$ [4], where λ_{res} represents the resonance wavelength at the low optical input power without self-heating, ΔI_{in} is the amount of input optical power change, n_g is the group refractive index, and *R* is the newly introduced self-heating coefficient representing change in the effective refractive index of the ring waveguide at the resonance wavelength, due to temperature change caused by input power increase. The numerical value of *R* can be determined to be $5.67\text{x}10^{-4}\,(\text{mW}^{-1})$ from Fig. 1(d) using the measured value of n_g of 3.84. The amount of red-shift in the transmission spectrum due to self-heating is proportional to the amount of optical power circulating in the ring waveguide at a given wavelength, or $\Delta\lambda_{\lambda} \sim \Delta\lambda_{res}(|A_{\lambda}|^2/|A_{res}|^2)$ [4]. $|A_{\lambda}|^2$ and $|A_{res}|^2$ represent the optical power in the ring waveguide at the given λ and the resonance wavelength, respectively, and their ratio can be calculated with the Si MRM model based the coupled-mode theory [4],[5]. Solid lines in Fig. 1(c) show calculated transmission spectra at different optical powers. As can be seen, they match very well with the measurement results.

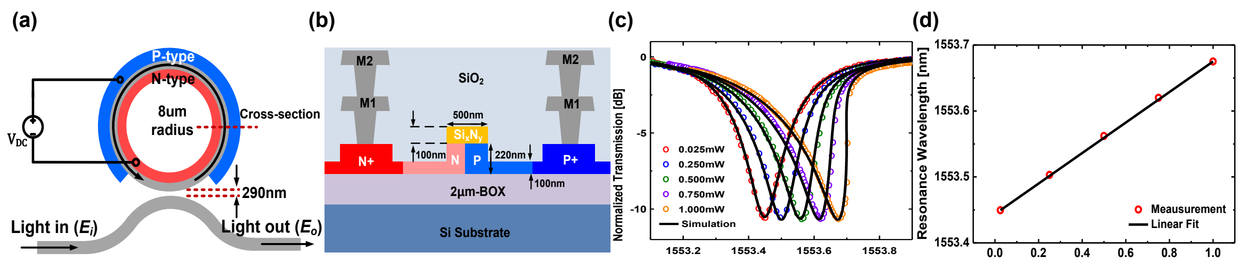

Figure 1: (a) Structure and (b) cross-section of Si MRM. (c) Transmission spectra of Si MRM at five different input optical powers. (d) Measured resonance wavelength at five different input optical powers.

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TABLE I EXTRACTED SI MRM PARAMETERS

λ_{res} (nm)	$n_{res,o}$	n_g	τ (ps)	τ_e (ps)	τ_l (ps)	R (mW^{-1})
1553.449	2.657814	3.84	8.8098	24.7103	13.6909	5.67×10^{-4}

Table 1 lists the numerical values for the parameters in our Si MRM model, all of which are determined by fitting the coupled-mode model into the measured Si MRM transmission spectra. τ is the total decay time constant for the optical energy in the ring waveguide, τ_e and τ_l are the optical energy decay time constant due to coupling and ring waveguide loss, respectively. $n_{res,o}$ is the effective refractive index at the resonance wavelength without self-heating.

Using the small-signal approximation of the coupled-mode theory, the Si MRM modulation frequency response in the s-domain can be given as [6]

$$H(s) = \frac{P_{out}(s)}{v(s)} = \frac{4P_{in}}{n_{res,o}} \cdot \frac{\delta n_{eff}}{\delta v} \cdot \frac{\omega_{res,o} D/\tau_e}{D^2 + 1/\tau^2} \cdot \frac{s + 2/\tau_l}{s^2 + (2/\tau)s + D^2 + 1/\tau^2}, \quad (1)$$

where P_{in} is input optical power, $\delta n_{eff}/\delta v$ is the rate of effective index change due to voltage modulation, which is determined by measurement, and $\omega_{res,o}$ is the resonance angular frequency without self-heating. D is the amount of detuning, or the angular frequency separation for the input light from the resonance ($D = \omega_{in} - \omega_{res}$). Since the time constant for self-heating is much larger than those time constants used for Si MRM frequency response model [7], the influence of self-heating on (1) can be determined by considering only the change in D due to the resonance wavelength shift caused by self-heating. Fig. 2(b) shows the modulation frequency responses at three different input powers for a Si MRM device whose transmission spectra are shown in Fig. 2(a). The input wavelength used for Fig. 2(b) is indicated as a dotted line in Fig. 2(a). As can be seen in the figures, modulation frequency responses change significantly for different input powers due to self-heating. Solid lines in Fig. 2(b) represent by the calculated results using (1) with different D values due to self-heating given as $D = \omega_{in} - \omega_{res,o}(1 - \frac{R\Delta I_{in}}{n_g + R\Delta I_{in}})$. As can be seen, the calculated results agree very well with the measurement results, confirming the accuracy of our model.

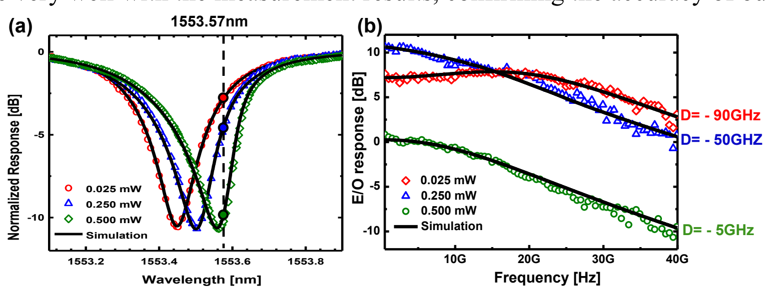

Figure 2: (a) Transmission spectra of Si MRM at three different input optical powers. (b) Modulation frequency responses at three different input optical powers for the same input wavelength.

These results show that very precise control of the input wavelength is required in order to have desired Si MRM modulation characteristics when input optical power can change. The newly introduced self-heating coefficient, R, allows precise modeling of transmission spectra and modulation frequency responses at any input optical power and can be used as a Si MRM parameter in photonic devices PDKs that Si photonics foundry services provide to foundry users. This work was supported by National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (2015R1A2A2A01007772).

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