Research article

Rishi Maiti, Rohit A. Hemnani, Rubab Amin, Zhizhen Ma, Mohammad H. Tahersima, Tom A. Empante, Hamid Dalir, Ritesh Agarwal, Ludwig Bartels and Volker J. Sorger*

A semi-empirical integrated microring cavity approach for 2D material optical index identification at 1.55 μm

<https://doi.org/10.1515/nanoph-2018-0197>

Received November 15, 2018; revised December 28, 2018; accepted December 31, 2018

Abstract: Atomically thin 2D materials such as transition metal dichalcogenides (TMDs) provide a wide range of basic building blocks with unique properties, making them ideal for heterogeneous integration with a mature chip platform for advances in optical communication technology. The control and understanding of the precise value of the optical index of these materials, however, is challenging, as the standard metrology techniques such as the millimeter-large ellipsometry is often not usable due the small lateral 2D material flake dimension. Here, we demonstrate an approach of passive tunable coupling by integrating few layers of MoTe_2 onto a microring resonator connected to a waveguide bus. We find the TMD-to-ring circumference coverage length ratio required to precisely place the ring into a critical coupling condition to be about 10% as determined from the variation of spectral resonance visibility and loss as a function of TMD coverage. Using this TMD-ring heterostructure, we further demonstrate a semiempirical method to determine the index of a 2D material (n_{MoTe_2} of $4.36 + 0.011i$) near telecommunication-relevant wavelength. The placement, control, and optical property understanding of

2D materials with integrated photonics pave the way for further studies of active 2D material-based optoelectronics and circuits.

Keywords: heterogeneous integration; 2D materials; TMDs; microring resonator; 2D printer; coupling coefficients.

1 Introduction

The ever-increasing demand for high-performance computing requires efficient on-chip interconnects [1]. Hence, intensive efforts have been devoted to achieving compact photonic components such as light source, detector, and modulator, which is challenging to realize within one single monolithic platform. In contrast, the heterogeneous integration of 2D materials on silicon (Si) offers a promising solution, as it provides a highly tunable and functional platform for a variety of optoelectronic devices [2–8]. To properly aid the design and anticipate device performance, knowledge of the complex refractive index is fundamentally important. Recently, a few groups have measured the optical index of transition metal dichalcogenides (TMDs) using ellipsometry [9, 10]. However, there are two challenges in using ellipsometry to determine the refractive index of TMDs and devices fabricated thereof: (a) the typical optoelectronic device dimensions being on the order of micrometers are too small to be probed by ellipsometry and (b) the state-of-the-art of TMD synthesis does not allow to grow sufficiently uniform large films with high quality yet. Even if that could be solved, the thermal budget may not sufficient to allow for direct chemical vapor deposition (CVD) growth on the actual device or circuit substrate. Also, even if wafer-scale growth would be possible, the subsequent required etch step will affect the surface-sensitive optical index of these 2D materials. As a result, determining the refractive index of TMDs

*Corresponding author: Volker J. Sorger, Department of Electrical and Computer Engineering, George Washington University, Washington, DC 20052, USA, e-mail: sorger@gwu.edu
 Rishi Maiti, Rohit A. Hemnani, Rubab Amin, Zhizhen Ma and Mohammad H. Tahersima: Department of Electrical and Computer Engineering, George Washington University, Washington, DC 20052, USA. <https://orcid.org/0000-0002-9236-5124> (R. Maiti)
 Tom A. Empante and Ludwig Bartels: Chemistry and Materials Science and Engineering, University of California, Riverside, CA 92521, USA
 Hamid Dalir: Omega Optics, Inc., 8500 Shoal Creek Boulevard, Building 4, Suite 200, Austin, TX 78757, USA
 Ritesh Agarwal: Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia, PA 19104, USA

in situ is a requirement that we address here using integrated photonic microcavities.

2D materials are actively investigated due to their interesting properties in various fields of physics, chemistry, and materials science, starting with the isolation of graphene from graphite [11]. Although graphene shows many exceptional properties, its lack of an electronic bandgap has stimulated the search for alternative 2D materials with semiconducting characteristics [12–16]. TMDs, which are semiconductors of the type MX_2 , where M is a transition metal atom (such as Mo or W) and X is a chalcogen atom (such as S, Se, or Te), provide a promising alternative. 2D TMDs exhibit unique physical properties such as indirect to direct bandgap transition [17], quantum confinement with photonic crystal cavity [18–20], strong spin-orbit coupling [21], and high exciton binding energies [22] compared to their bulk counterparts, making them versatile building blocks for optical modulators or reconfiguration in an Si-based hybrid platform.

Here, we demonstrate the heterogeneous integration of a few layers of MoTe_2 on an Si microring resonator (MRR) platform. The interaction between TMDs and the Si MRR provides novel tunable coupling phenomena that can be tuned from the overcoupling to the undercoupling regime via a critical coupling condition by means of altering the ring effective index via the integration of TMDs. We analyze the coupling physics and extract fundamental parameters, such as quality factor, visibility, and transmission at resonance, as a function of MoTe_2 coverage on the ring. We find a critical coupling coverage ratio value ($\sim 10\%$) for a given ring resonator, which is relevant for device functionality. Furthermore, we determine the index ($n_{\text{MoTe}_2} = 4.36 + 0.011i$) of the few-layered MoTe_2 at $1.55 \mu\text{m}$ wavelength in a semiempirical approach using the ring resonator as an index sensor platform.

2 Results

To obtain an understanding of phase modulation in heterogeneous integrated systems, it is important to understand the interaction between TMDs and an MRR, as the spectral distance of each TMD's exciton relative to the waveguide probing wavelength (here, $\lambda_{\text{op}} = 1550 \text{ nm}$) is noncoincidental; thus, the real versus imaginary part index decay away from the exciton resonance has a different impact on the telecom-operating photonic structures. Unlike other larger-bandgap TMDs (for example, MoS_2 , WS_2 , MoSe_2 , and WSe_2), the optical bandgap of a few-layered MoTe_2 ($\sim 0.9 \text{ eV}$) is smaller than the bandgap

of Si ($\sim 1.1 \text{ eV}$) and allows a facile integration with an Si photonic platform. Here, the aim is to improve the waveguide bus-to-ring coupling efficiency by shifting the phase through the introduction of a few-layered MoTe_2 flakes on top of the resonator (Figure 1A–C). By varying the MoTe_2 coverage length, we observe a tunable coupling response. To achieve TMD loading of the rings, we use a precise and cross-contamination-free transfer using the 2D printer method recently developed [23]. The transmission spectra before and after MoTe_2 transfer reveal a definitive improvement of coupling in terms of visibility defined as the transmission amplitude ratio ($T_{\text{max}}/T_{\text{min}}$) upon TMD loading (Figure 1D). This hybrid device shifts toward the critical coupling regime compared to before transfer where it was overcoupled.

We fabricated a set of ring resonators with different percentages of MoTe_2 coverage between 0% and 30% (Figure 2), which allowed us to extract different parameters to understand coupling physics. The cavity quality (Q) factor is found to decrease from 1600 to 900 as the ring coverage is raised from 0 to 27% (Figure 2A). We attribute this as a gradual increase of loss arising from both MoTe_2 absorption near its band edge corresponding to indirect bandgap of 0.88 eV [24] and the small impedance mismatch between bare and TMD-covered sections of the rings. In contrast to the monotonic behavior of the quality factor, the minimum transmission (T_{min}) at resonant wavelength initially decreases until 10% coverage is reached and then increases for higher coverage (Figure 2B). The visibility ($T_{\text{max}}/T_{\text{min}}$) shows the opposite trend being maximal near 10% of TMD coverage (Figure 2C). In combination, these findings indicate the tunability of the coupling condition by means of varying TMD coverage.

The performance of a ring resonator is determined by two coefficients: the self-coupling coefficient (r), which specifies the fraction of the light transmitted on each pass through the coupler, and the roundtrip transmission coefficient (a), which specifies the fraction of the light transmitted per pass around the ring. For the critical coupling condition, i.e. when the coupled power is equal to the power loss in the ring $1 - a^2 = k^2$ or $a = r$ (k = cross-coupling coefficient), the transmission at resonance becomes zero. At this point, the difference ($|a - r|$) is found to be minimum at $\sim 10\%$ of the coverage (Figure 2D), suggesting close to critical coverage as $|a - r|$ is inversely proportional to the square root of the visibility term [25]. Thus, the coupling condition is tunable from the overcoupled regime ($r < a$) to the undercoupled regime ($r > a$) via the critical coupled regime ($r = a$) as a function of TMD coverage. Being able to operate at critical coupling is important for active device functionality; for instance, the extinction

Figure 1: TMD-loaded MRR.

(A) Schematic representation and (B) optical microscopy image of a taped-out Si photonic chip with grating coupler. Optical micrograph of a grating coupler designed for TM mode at 1550 nm in the field of a view of 100× objective (inset). (C) Zoomed image of an MRR ($R=40\ \mu\text{m}$ and $W=500\ \text{nm}$) covered by an MoTe_2 flake of length (l) precisely transferred using our developed 2D printer technique. (D) Transmission output before and after the transfer of MoTe_2 showing an improvement of coupling efficiency as it brings the device close to the critical coupled regime after the transfer of the TMD layer.

ratio of an MRR-based electro-optic modulator is maximized at critical coupling [26, 27].

To understand the coupling mechanism of a ring resonator, it is important to extract and distinguish coupling coefficients (a and r), as they are governed by different factors in design and fabrication. However, it is not possible to decouple both the coefficients without additional information, as a and r can be interchanged [Eq. (1)]. The transmission from an all-pass MRR (Figure 3A) is given by

$$T_n = \frac{a^2 + r^2 - 2ar \cos \varphi}{1 + r^2 a^2 - 2ar \cos \varphi} \quad (1)$$

where φ is the roundtrip phase shift and a is the roundtrip transmission coefficient related to the power attenuation coefficients by

$$a^2 = \exp(-\alpha_{\text{Si}}(2\pi R - l)) * \exp(-\alpha_{\text{TMD-Si}} * l) \quad (2)$$

where l is the TMD coverage length and α_{Si} and $\alpha_{\text{TMD-Si}}$ are the linear propagation losses for Si waveguide and

TMD-transferred portion of the Si waveguide in the ring, respectively. We find the propagation loss for Si and TMD-Si to be 9.7 dB/cm (Figure S13) and 0.4 dB/ μm (Figure 3B), respectively, via the cutback method at 1550 nm.

Inserting these values into Eq. (2), we find the roundtrip transmission coefficient (a) to be tuned as a function of TMD coverage (Figure 3C). The variation of a from 0.97 to 0.01 as a function of coverage confirms the transition from the overcoupled to the undercoupled regime as $a=1$ suggests that there is no loss in the ring. Hence, the loss tunability in MRRs can be manipulated accordingly by controlling the coverage length [28]. The MRR transmission at resonance leads to the form: $T_{n,\text{res}} = \left(\frac{a-r}{1-ar} \right)^2$; therefore, the critical coverage ($a=r$) anticipates zero-output transmittance. Hence, for a given MRR (fixed k^2), the critical coverage value could be determined assuming lossless coupling ($r^2 + k^2 = 1$; Figure 3D).

Si-based MRRs provide a compact and ultra-sensitive platform as refractive index sensor to find an unknown

Figure 2: TMD-loaded tunable coupling effect.

Variation of (A) Q factor, (B) minimum transmission ($T_{\min}$), (C) visibility ($T_{\max}/T_{\min}$), (D) difference between the self-coupling coefficient and the roundtrip transmission coefficient $|a - r|$ as a function of MoTe_2 coverage. The monotonic decrease of Q factor suggests increasing loss for higher coverage, i.e. more transferred TMD. Tunability of coupling effect, i.e. transition from the overcoupled to the undercoupled regime via critical coupled condition (dashed vertical line), is evident from the variation of $T_{\min}$, $T_{\max}/T_{\min}$, and $|a - r|$. (E) Corresponding figures for different coverage (bare ring, 6% and 22%) showing the advantages of precise transfer by 2D transfer methods.

index of the 2D materials at telecom wavelength ($1.55 \mu\text{m}$). In essence, the shift in resonant wavelength can be used to sense the optical properties affecting entities on the Si core or the cladding [29]. We observe a gradual resonance red shift from bare to increased coverage of MoTe_2 of 4.5%, 10%, and 17%, respectively (Figure 4A). The change in resonant wavelength (λ_{res}) of an MRR independent on group index, which takes into account the dispersion of the waveguide, can be defined as $n_g = n_{\text{eff}} - \lambda_0 \frac{dn_{\text{eff}}}{d\lambda}$ for our

case, as the resonance shift occurs over a narrow wavelength range, where $dn_{\text{eff}}/d\lambda < 1$, considering first-order dispersion term, we approximate n_g as n_{eff} [30, 31]. Therefore, the change in effective mode index (Δn_{eff}) is related to change in resonance ($\Delta\lambda$) following $\Delta n_{\text{eff}} = \frac{\Delta\lambda}{\lambda_{\text{res}}} * n_{\text{eff,control}}$,

where $n_{\text{eff,control}}$ is the effective mode index for Si MRR (i.e. without any TMD flakes transferred). The effective index for the control sample (Si ring + SiO_2 cladding) can be found from FEM eigenmode analysis choosing the TM-like mode in correspondence with our TM grating designs used in measurements (Figure SI4). We map out the resonance shift ($\Delta\lambda$) as a function of MoTe_2 coverage (Figure 4B, i) for needed calibration to determine the unknown index using a semiempirical approach. The positive change in the effective index (Δn_{eff}) as a function of MoTe_2 coverage relates to an increased effective mode index with TMD transfer (Figure 4B, ii) and the corresponding red shifts thereof.

Now, we obtain a resonance shift of 1 nm for 4% coverage, which gives a corresponding change in effective index of 0.001 (Figure 4B). At this point, it is important to establish the relation between the effective mode index and the refractive index of the unknown TMDs. As, in our case, the MRR is partially covered by MoTe_2 flakes and the resonance shift arises from a change in effective mode index due to the change in coverage length, the effective refractive index of the ring can be formulated as an effective length-fraction index via

$$n_{\text{eff,ring}} = \frac{(2\pi R - l) * n_{\text{eff,control}} + l * n_{\text{eff}}}{2\pi R} \quad (3)$$

where R is the radius of the ring and l is the MoTe_2 coverage length. Using Eq. (3), it is straightforward to find n_{eff} after TMD transfer.

Once n_{eff} is known, we can find the effective index of the heterogeneous optical mode [Si-on-insulator (SOI) plus TMD] through eigenmode analysis for device geometry and provide experimentally measured thickness values of the flake (Figure SI5). By sweeping the value of the TMD (n_{TMD} range = [3.5, 5]) material index in cross-sectional eigenmode analysis of the waveguide structure in the MoTe_2 transferred section of the ring (Figure 4C), we can match the numerically obtained effective index with that found from aforementioned experimental results. We find the index of the bulk MoTe_2 material to be 4.36 (Figure 4D). This index value is closely aligned with reported values in previous studies for bulk MoTe_2 [32]. We also find the imaginary part of the material index from the cutback method varying flake sizes

Figure 3: Coupling coefficients for TMD integrated hybrid Si MRR.

(A) Schematic representation of MRR showing self-coupling coefficient (r), cross-coupling coefficient (k), and roundtrip transmission coefficient (a), where the ring is partially covered by a MoTe₂ flake. (B) Propagation loss ($\alpha_{\text{TMD-Si}}$) for TMD-covered portion of the ring found to be 0.4 dB/ μm using cutback measurement. (C) Tunability of roundtrip transmission coefficient explains the exponential decrease as a function of flake coverage. (D) Relationship between critical coverage (%) and power coupling coefficient (k^2) assuming lossless coupling ($r^2 + k^2 = 1$).

to be ~ 0.011 . This semiempirical approach has several advantages over conventional ellipsometric technique to determine the refractive index of the unknown materials; for instance, in ellipsometry, large uniform flakes (few millimeters to centimeters) are needed as the beam spot size is generally large, which are still challenging to obtain with uniform properties across such scales. However, for the method presented here, small TMD flakes (~ 500 nm) can be measured. In fact, the limit of this technique is not bounded by the MRR waveguide width, as a partial coverage of the top waveguide is also possible to measure but with linear phase shift scaling with respect to the area covered. Besides this, to determine the refractive index of the materials from the ellipsometry data, the experimental data need to be fitted by an exact physical model that bears ambiguity and thus introduces additional inaccuracy.

3 Conclusion

We have studied the interaction between a few layers of MoTe₂ and Si MRR for the first time. We observed the tunability of the coupling strength, i.e. the ring resonator can be tuned from the overcoupled to the undercoupled regime while passing through the critical coupled point. The underlying physical mechanism of tunable coupling can be explained by extracting different coupling coefficients as a function of coverage length. For the material properties examined here, the critical coverage value for a given MRR is $\sim 10\%$. We further demonstrated a semi-empirical approach to determine the index of miniscule (~ 500 nm) of TMD material flakes using the index sensitivity of the ring resonator. These findings along with the developed methodology for placing MRRs into critical coupling for active device functionality and determining

Figure 4: Ring resonator as refractive index sensor.

(A) Normalized transmission spectra for different coverage showing gradual red shift. (B) Variation of resonance shift ($\Delta\lambda$) and effective index change (Δn_{eff}) extracted from (A) as a function of MoTe₂ coverage length. The mapped-out resonance shift as a function of coverage length provides the calibration curve to determine the unknown index of the TMDs. (C) Mode profile ($|E|$) for the portion of the ring with MoTe₂ transferred flakes from eigenmode analysis. (D) FEM results for effective index n_{eff} versus the MoTe₂ index n_{TMD} to extract the material index from experimental results. The green dashed line exhibits the obtained MoTe₂ index from our results as 4.36.

the refractive index of 2D materials could be useful tools in future heterogeneous integrated photonic and optoelectronic devices [33]. This developed technique could also be used to determine the optical refractive index of monolayer 2D materials, which is challenging with traditional techniques due to lateral TMD flake size, and the atomic thickness of these materials.

4 Methods

The Si waveguide and MRR system was fabricated using an SOI substrate, where the Si device layer is 220 nm and the oxide layer is 2 μm thick. The pattern was defined

using electron beam lithography with negative photoresist (HSQ). Then, a Bosch etching process was performed to etch Si and the HSQ layer was performed as an etching mask during the Bosch process. After etching, the HSQ residue was removed using HF. Then, the precise transfers of TMD materials were performed using our developed 2D printer method (Figure SI1) after the deposition of ~ 300 nm SiO₂ cladding layer on Si MRR by plasma-enhanced CVD (Versalin PECVD). It provides a fast and cross-contamination-free transfer of flakes having different lengths and thickness obtained from mechanically exfoliated TMD crystals. The precise transfer of the TMD flakes without troubling neighboring devices is key here. Therefore, the role of the microstamper is a critical aspect for the transfer as for a successful transfer of a single flake

the effective contact area (A_{eff}) of the microstamper must be greater than the flake area (A_{flake}).

The experimental setup for measuring the hybrid TMD-Si devices is shown in Figure SI2. Briefly, light from a broadband source (AEDFA-PA-30-B-FA) is injected into the grating coupler optimized for the TM-mode propagation in the waveguide. The light output from the MRR is coupled to the output fiber by a similar grating coupler and detected by the optical spectral analyzer (OSA202).

Acknowledgments: V.J.S. and L.B. were supported by the AFOSR (Funder Id: <http://dx.doi.org/10.13039/1000000181>, award number FA9550-17-1-0377) and the NSF Materials Genome Initiative (Funder Id: <http://dx.doi.org/10.13039/1000000001>, award number NSF DMREF 14363300/1455050). R.A. and V.J.S. were supported by the ARO (Funder Id: <http://dx.doi.org/10.13039/1000000183>, award number W911NF-16-2-0194).

References

- [1] Alduino A, Paniccia M. Wiring electronics with light. *Nat Photonics* 2007;1:153–5.
- [2] Rao CNR, Sood AK, Subrahmanyam KS, Govindaraj A. Graphene: the new two-dimensional nanomaterial. *Angew Chem Int Ed* 2009;48:7752–77.
- [3] Novoselov KS, Jiang D, Schedin F, et al. Two-dimensional atomic crystals. *Proc Natl Acad Sci* 2005;102:10451–3.
- [4] Castro Neto AH, Peres NMR, Novoselov KS, Geim AK. The electronic properties of graphene. *Rev Mod Phys* 2009;81:109–62.
- [5] Amin R, Ma Z, Maiti R, et al. Attojoule-efficient graphene optical modulators. *Appl Opt* 2018;57:D130–40.
- [6] Tahersima MH, Birowosuto MD, Ma Z, et al. Testbeds for transition metal dichalcogenide photonics: efficacy of light emission enhancement in monomer vs dimer nanoscale antennae. *ACS Photonics* 2017;4:1713–21.
- [7] Maiti R, Sinha TK, Mukherjee S, Adhikari B, Ray SK. Enhanced and selective photodetection using graphene-stabilized hybrid plasmonic silver nanoparticles. *Plasmonics* 2016;11:1297–304.
- [8] Tahersima MH, Sorger VJ. Enhanced photon absorption in spiral nanostructured solar cells using layered 2D materials. *Nanotechnology* 2015;26:344005.
- [9] Liu HL, Shen CC, Su SH, Hsu CL, Li MY, Li LJ. Optical properties of monolayer transition metal dichalcogenides probed by spectroscopic ellipsometry. *Appl Phys Lett* 2014;105:201905.
- [10] Zhang H, Ma Y, Wan Y, et al. Measuring the refractive index of highly crystalline monolayer MoS₂ with high confidence. *Sci Rep* 2015;5:8440.
- [11] Geim AK, Novoselov KS. The rise of graphene. *Nat Mater* 2007;6:183–91.
- [12] Manzeli S, Ovchinnikov D, Pasquier D, Yazyev OV, Kis A. 2D transition metal dichalcogenides. *Nat Rev Mater* 2017;2:17033.
- [13] Splendiani A, Sun L, Zhang Y, et al. Emerging photoluminescence in monolayer MoS₂. *Nano Lett* 2010;10:1271–5.
- [14] Mak KF, Shan J. Photonics and optoelectronics of 2D semiconductor transition metal dichalcogenides. *Nat Photonics* 2016;10:216.
- [15] Radisavljevic B, Radenovic A, Brivio J, Giacometti IV, Kis A. Single-layer MoS₂ transistors. *Nat Nanotechnol* 2011;6:147.
- [16] Mak KF, Lee C, Hone J, Shan J, Heinz TF. Atomically thin MoS₂: a new direct-gap semiconductor. *Phys Rev Lett* 2010;105:136805.
- [17] Chowdhary RK, Maiti R, Ghorai A, Midya A, Ray SK. Novel silicon compatible hetero-junction using Li-ion intercalated p-WS₂ layers exhibiting broadband and superior responsivity. *Nanoscale* 2016;8:13429–36.
- [18] Wu S, Buckley S, Jones AM, et al. Two-dimensional metal-chalcogenide films in tunable optical microcavities. *Nano Lett* 2014;14:7003–8.
- [19] Gan X, Gao Y, Fai Mak K, et al. Controlling the spontaneous emission rate of monolayer MoS₂ in a photonic crystal nanocavity. *Appl Phys Lett* 2013;103:181119.
- [20] Fryett TK, Seyler KL, Zheng J, Liu C-H, Xu X, Majumdar A. Silicon photonic crystal cavity enhanced second-harmonic generation from monolayer WSe₂. *2D Mater* 2017;4:015031.
- [21] Xu X, Yao W, Xiao D, Heinz TF. Spin and pseudospins in layered transition metal dichalcogenides. *Nat Phys* 2014;10:343.
- [22] Low T, Chaves A, Caldwell JD, et al. Polaritons in layered two-dimensional materials. *Nature Mater* 2017;16:182.
- [23] Hemnani RA, Carfano C, Tischler JP, et al. Towards a 2D printer: a deterministic cross contamination-free transfer method for atomically layered materials. *2D Mater* 2019;6:15006.
- [24] Lezama IG, Ubaldini A, Longobardi M, et al. Surface transport and band gap structure of exfoliated 2H MoTe₂ crystals. *2D Mater* 2014;1:021002.
- [25] McKinnon WR, Xu DX, Storey C, et al. Extracting coupling and loss coefficients from a ring resonator. *Opt Express* 2009;17:18971–82.
- [26] Phare CT, Lee YH, Cardenas J, Lipson M. Graphene electro-optic modulator with 30 GHz bandwidth. *Nat Photonics* 2015;9:511.
- [27] Qiu C, Gao W, Vajtai R, Ajayan PM, Kono J, Xu Q. Efficient modulation of 1.55 μm radiation with gated graphene on a silicon microring resonator. *Nano Lett* 2014;14:6811–5.
- [28] Ding Y, Zhu X, Xiao S, et al. Effective electro-optical modulation with high extinction ratio by a graphene-silicon microring resonator. *Nano Lett* 2015;15:4393–400.
- [29] White IM, Fan X. On the performance quantification of resonant refractive index sensors. *Opt Express* 2008;16:1020–8.
- [30] Tsigaridas GN. A study on refractive index sensors based on optical micro-ring resonators. *Photonic Sens* 2017;7:217.
- [31] Kwon M-S, Steier WH. Microring-resonator-based sensor measuring both the concentration and temperature of a solution. *Opt Express* 2008;16:9372–7.
- [32] Froehlicher G, Lorchat E, Berciaud S. Direct versus indirect band gap emission and exciton-exciton annihilation in atomically thin molybdenum ditelluride (MoTe₂). *Phys Rev B* 2016;94:085429.
- [33] Amin R, Suer S, Ma Z, et al. Active material, optical mode and cavity impact on nanoscale electro-optic modulation performance. *Nanophotonics* 2017;7:455–72.

Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2018-0197>).