Research article

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Resonance-enhanced all-optical modulation of WSe₂-based micro-resonator

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Abstract: Two-dimensional material tungsten diselenide (WSe₂) nanosheets are coated on a microfiber knot resonator (MKR) to achieve an all-optical power modulation functionality. On account of the strong absorption property of WSe₂ and the resonance enhancement properties of MKR, the transmitted optical power of signal light within the WSe₂-based MKR can be effectively modulated. The sensitivities of light-control-light experiments with 405- and 660-nm lasers are as high as 0.32 and 0.12 dB/mW, respectively. The sensitivities and power tuning can be enhanced by a higher resonance Q and a larger extinction ratio of MKR. In terms of the response time, the average rise and fall times are 3.5/3.7 and 3.5/4 ms with 405- and 660-nm lasers, respectively. This proposed structure is expected to achieve potential applications in all-fiber-optic-based tunable device such as optical modulator, detector, and so on.

Keywords: two-dimensional material; tungsten diselenide; resonance enhance; microfiber knot resonator.

1 Introduction

Optical modulators are key components on modern communication system. One of the ways to develop optical modulators is using optic-fiber for its high compatibility with all-optical circuit. Optical fiber is one of the most important information transmission media [1]. Tapered microfiber (MF) can be obtained by pulling standard fiber with heat-flaming method [2], which reduces the cladding thickness to make evanescent wave overflow the surface of fiber. Thus, an enhancement of interaction between light and matter can be achieved. Microfiber knot resonator (MKR) can be obtained by knotting MF. Compared with common MF, it has a stable structure and remarkable resonance characteristics with high Q factor, which makes it a better structure for optical modulation [3]. It has been currently applied in the field of sensors [4], modulators [5], lasers [6], accelerometers [7], and so on. Attached to optical materials that can be modulated by laser pumping or applied voltage, MKR devices with rapid modulation and high sensitivity can be obtained.

Two-dimensional materials that can be optically or electrically modulated are ideal for combining with fiber-based devices [8]. Typical two-dimensional materials such as graphene [9], silicene [10], phosphorene [11], arsenene, and antimonene [12] have garnered tremendous interest for their unique optical properties. Graphene can be applied in both microwave and optical band [9] and act an important role in fiber laser for ultrahigh-repetition-rate pulse [13]. Silicene has been further studied because of its high performance in photoelectronics properties [10]. Phosphorene, allotrope of phosphorus, is developed for optoelectronic devices such as two-dimensional CMOS inverter [11], as well as phase modulation ability with a conversion efficiency of $0.029 \pi \text{ mW}^{-1}$ [14]. Arsenene with band gaps of greater than 2.0 eV is found potential in devices working under blue or UV light [12], while few-layer bis-muthene could be coated onto MF to fabricate an optical

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Kerr switcher [15] or all-optical phase and intensity modulator [16]. As to antimonene, it is investigated and exploited in all-optical signal processor [17], modulator for Q-switched laser [18], and optical saturable absorber on ultrafast photonics processing [19] with high optical nonlinearity and excellent optical response. Recently, low-dimensional perovskite has already been recognised for nanophotonics applications because of its significance in optoelectronics [20], whereas MXene Ti₃C₂T_x has been investigated and employed in wavelength converter at the telecommunication band [21]. Two-dimensional metal-halide perovskite has been found a desired promise in broadband optical limiting and ultrafast photonic devices [22]. In addition, transition metal dichalcogenides (TMDs) with structure of AB₂ are also a kind of cutting-edge materials [23], where *A* represents elements in the D and DS regions of the periodic table, whereas *B* represents diselenides, such as WS₂ [24], NbSe₂ [25], MoSe₂ [26], and TaSe₂ [27]. As optoelectronic-materials have various properties, it is proposed to exactly exploit potential applications from a particular material.

Tungsten diselenide (WSe₂), a family member of TMDs, has appealing properties such as high absorption of visible light, high mobility [28], low thermal conductivity [29], and modest band gap of ~1.35 eV [30], which makes it an ideal material for light modulation. Compared with graphene, WSe₂ is a kind of semiconductor with direct band gap for a better optoelectronics performance. At present, WSe₂ has been investigated deeply and developed to numerous optoelectronics applications. For example, large-size and high-quality WSe₂ nanosheets can be prepared by introducing hydrogen in reaction chamber [31]. In addition, this material can be combined with other materials such as MoSe₂ [32] and MoS₂ [33] in the p–n junction. Recently, it has been developed

as field-effect transistors [34, 35] mainly. These unique properties of WSe₂ can be applied in a light–control–light optical device.

Herein, the article demonstrates that an MKR structure covering WSe₂, in which the transmitted power can be modulated by pump light (405/660 nm), can realise light–control–light function. Under the 405-nm external pump laser, the largest sensitivity is 0.32 dB/mW, whereas the response rise/fall time is 3.5/3.5 ms. In terms of the 660-nm laser, the largest sensitivity is 0.12 dB/mW, whereas the response time is 3.7/4 ms corresponding to rise/fall time. Furthermore, this device provides a direct evidence that the sensitivities for optical modulation are boosted by the enhancement of resonator with a higher resonance Q and a larger extinction ratio (ER).

2 Device fabrication

The fabrication of the WSe₂-coated MKR structure and the characterization analysis of WSe₂ nanosheets are presented in this section. Figure 1A shows the diagrammatic drawing of WSe₂-coated MKR structure.

The MF with strong evanescent wave leaking is fabricated by stretching an SMF-28 (Coring) through heat-flame taper-drawing approach [2]. With adjustable station assisting, the MF is transformed into an MKR. In order to exclude irrelevant factors such as air agitation and humidity, the MKR is attached to an MgF₂ slide and then placed in a dry box. Figure 1B shows a microscopic image of the MKR structure whose ring area (corresponding to the MF with a diameter of ~10 μm) is viewed in the inset, from which it can be ensured that the MKR has been fabricated into qualified structure. The length of the WSe₂ coating area (away from the knot region) is about one-fifth of the MKR. By connecting a tunable laser source (TLS) to one

Figure 1: The schematic diagram and transmission spectrum of the device.

(A) Diagrammatic drawing of the WSe₂-coated MKR structure. (B) Microscopic of the MKR structure with a loop diameter of $D = 1038 \mu\text{m}$, and the inset shows enlarged image of the ring area with a diameter of $d = 10 \mu\text{m}$. (C) Transmission spectrum of the MKR with the largest ER of 13.6 dB at the resonance around 1565.9 nm.

end of the MKR, while the other end is connected to an optical spectrum analyser (OSA), the transmission property of the MKR is measured as shown in Figure 1C. It can be speculated that the MKR owns a free spectrum range (FSR) of ~ 0.65 nm, a Q factor of $\sim 18,204$, and an ER of ~ 13.6 dB around 1565.9 nm.

The WSe₂ dispersion we exploit here is fabricated by lithium ion intercalation exfoliation method with a concentration of 1 mg/ml. In order to further investigate the property of WSe₂ nanosheets, Raman and UV-Vis absorption spectra are performed as shown in Figure 2A and B.

Figure 2A shows the UV-Vis absorption spectrum of the WSe₂ nanosheets where relatively strong absorption can be observed on wavelengths of around 400 nm. Therefore, 405-nm pump light will be employed as external excitation in the following experiments. As a comparison, 660-nm pump light will play the same role. Raman spectrum is shown in Figure 2B to further investigate the characterization of the WSe₂ nanosheets, from which a prominent peak (E_{2g}^1 and A_g^1) is located at around 250.6 cm^{-1} [36, 37]. The frequency difference of the E_{2g}^1 and A_g^1 modes is too small to distinguish, explaining the appearance of only one peak in the spectrum. The E_{2g}^1 mode originates from the out-phase vibrations of two selenium (Se) atoms relative to tungsten (W) atom, while the vibration of Se atoms in an opposite direction to W atom contributes to the A_g^1 mode [38, 39].

The WSe₂ nanosheets are then deposited on the MKR structure by covering the WSe₂ dispersion. The dispersion is transferred onto the MF area away from the knot, ensuring that the deposition of the WSe₂ films increases the loss factor of the ring [40]. Hence, it primarily changes the transmission amplitude of the resonance. Consequently, the WSe₂-coated MKR structure is fabricated in a stable state once the dispersion dries out.

Figure 2C and its inset depict the scanning electron microscopy (SEM) image of the fabricated WSe₂-coated MKR, which means that WSe₂ films are coated effectively on the fibre with a diameter of $\sim 10\text{ }\mu\text{m}$. As shown in Figure 2D, the profile of the MF region is imaged by SEM, which deduces that the thickness of the WSe₂ films is ~ 254 nm.

3 Experimental details, results, and discussion

In this section, the light-control-light properties of MKR coated with and without WSe₂ are presented. Figure 3A shows the experimental setup where the 405-/660-nm lasers are chosen as the external pump sources. As shown in Figure 2A, the absorption of 405-nm light is significantly higher than that of 660 nm. To make a comparison, the

Figure 2: Absorption and Raman spectra, SEM image of the device.

(A) Absorption spectrum and (B) Raman spectrum of WSe₂ nanosheets. (C) SEM image of the WSe₂-coated MKR structure with the inset showing the enlarged view of local position. (D) Profile SEM image of the MF with WSe₂ and the inset showing the enlarged view of WSe₂'s thickness of ~ 254 nm.

405- and 660-nm lasers are chosen in order to figure out whether the modulation efficiency is dependent on the absorption. The absorption spectrum of WSe₂ indicates that the WSe₂-coated MKR structure can be potentially operated in broadband wavelengths. The sample (MKR or MKR with WSe₂) is fastened inside a basin made by UV adhesive onto an MgF₂ substrate. Signal light from TLS (ANDO-AQ4321D, ~1520–1620 nm) is guided into the MKR structure and then connected to an OSA (YOKOGAWA-AQ6317C) from the other side. Therefore, by detecting the signal light, the sensing characterization of external light is able to be educed.

First, the experiments of transmitted power modulating are performed on bare MKR with the transmission spectrum as shown in Figure 3B and C. The optical transmitted spectrum with a regular shape shows the maximum Q of ~18,204 and the greatest ER of ~13.6 dB in the resonance wavelength (λ_{res}) of ~1565.9 nm. The spectrum changes rarely (less than 0.1 dB) with the 405-nm external pump laser illuminating from 0 to 22.6 mW, while the position of λ_{res} seldom moves.

Replacing the external pump by a 660-nm laser in Figure 3A, the following experiments of transmitted

power modulating are performed with power ordering at 0, 3.5, 8.4, 14.7, and 20 mW. The results are shown in Figure 3C where both the transmitted power and the λ_{res} position have little variation. The maximum relative variation under the laser power of 20 mW is less than 0.2 dB. It can be manifested from these experimental results that bare MKR is not qualified to realise modulation of transmitted optical power, which is aligned with what has been demonstrated in a similar research [41–43].

Applying the same experimental setup (as shown in Figure 3A) and the same light power variation, the signal light modulating with 405-nm laser is then performed on the WSe₂-coated MKR structure. Figure 4A and B depict the transmitted spectrums around 1584.3 and 1613.6 nm in wavelength. The result shows a higher power of 405-nm light leads to a larger variation of output optical power, reflecting in the increase of transmitted power corresponding to the decrease of resonance ER. In addition, the largest transmitted power change of ~7.7 dB is achieved around 1613.6 nm with the highest power. Meanwhile, the position of λ_{res} has a slight shift of ~0.03 nm.

By substituting the 405-nm laser with the 660-nm laser, experiments are then conducted on

Figure 3: Results of all-optical modulation experiments on the bare MKR.

(A) Experimental setup for light amplitude modulating by 405-/660-nm external pump light. Transmission spectrum of bare MKR under (B) 405-nm light illuminating with power of 0, 0.34, 6.13, 13.64, and 22.6 mW and (C) 660-nm light illuminating with power of 0, 3.5, 8.4, 14.7, and 20 mW.

the WSe₂-coated MKR sample. As shown on Figure 4C and D, with the increase of 660-nm pump light power, the optical output power increases, which is similar to the case of 405-nm light excitation. It might be revealed from the decrease of ER that external light excitation makes the coupling loss factor increase. As Figure 4D shows, around the wavelength of ~ 1613.6 nm, the largest variation of transmitted optical power is ~ 2.7 dB, and the λ_{res} red shift is ~ 0.03 nm.

As shown in the Table 1, several resonance positions with modulation functionality of 405- and 660-nm external light can be achieved.

To analyse the relationship between optical variation (ΔT) of 405-/660-nm light and pump power, the wavelength of 1613.6 nm, which has the largest sensitivities of 405- and 660-nm light, is selected. Figure 4E shows the linear fit of ΔT under 405- and 660-nm light versus pump power at the selected wavelength. The phenomena can be

Figure 4: Results of all-optical modulation experiments on the MKR coated with WSe₂.

Transmission spectrum of MKR coated with WSe₂ under 405-nm light illuminating with different power, including (A) 1583.7–1585.7 nm and (B) 1611.8–1613.9 nm in wavelength. Transmission spectrum of MKR coated with WSe₂ under 660-nm light illuminating with different power, including (C) 1583.7–1585.7 nm and (D) 1611.8–1613.9 nm in wavelength. (E) Linear fit of ΔT under 405- and 660-nm light versus pump power at wavelength of 1613.6 nm. Linear fit of sensitivity under 405- and 660-nm light versus (F) resonance Q and (G) ER for the selected resonance positions at $\lambda_{\text{res}} \sim 1584.3$ nm, $\lambda_{\text{res}} \sim 1584.9$ nm, $\lambda_{\text{res}} \sim 1585.5$ nm, $\lambda_{\text{res}} \sim 1612.4$ nm, $\lambda_{\text{res}} \sim 1613.0$ nm, $\lambda_{\text{res}} \sim 1613.6$ nm.

Table 1: Resonance Q, ER, ΔT , and the sensitivity with 405-/660-nm laser pumping.

λ_{res} (nm)	Q	405-nm laser			Q	660-nm laser		
		ER	ΔT (dB)	Sensitivity (dB/mW)		ER	ΔT (dB)	Sensitivity (dB/mW)
1584.3	36,320	21.0	4.25	0.148	31,064	18.2	2.00	0.083
1584.9	31,076	18.9	3.69	0.133	25,157	15.6	1.47	0.070
1585.5	27,327	17.0	3.21	0.118	19,102	14.3	1.05	0.048
1612.4	38,390	20.2	4.50	0.203	31,627	18.9	2.07	0.099
1613.0	47,441	22.9	6.69	0.270	36,660	20.1	2.20	0.110
1613.6	62,056	25.0	7.70	0.320	40,341	20.7	2.70	0.120

concluded that the sensitivity of 405-nm light is greater than that of the 660-nm light, which can be made out by the fact that WSe₂ nanosheets have a stronger absorption of 405-nm light than 660-nm light in accordance with Figure 2A.

A higher resonance Q and a larger ER lead to a larger sensitivity regardless of the wavelengths of external pump laser. As mentioned in Table 1, six resonances (as shown in the Figure 4A–D) are exploited here to analyse the relationship between resonance Q, ER, and sensitivity. Figure 4F shows the linear fit of sensitivities under 405- and 660-nm light versus resonance Q at the selected wavelengths. As shown in Figure 4F and G, the largest sensitivity of 405-nm power (~ 0.32 dB/mW) can be obtained with the greatest resonance Q ($\sim 62,056$) and ER (~ 25 dB). As to experiments under 660-nm light illuminating, the largest sensitivity of ~ 0.12 dB/mW can be obtained with the greatest resonance Q ($\sim 40,341$) and ER (~ 20.7 dB). A resonance with high Q and ER enables itself to have a great deal of light energy stored inside the structure, which enhances the light–matter interaction. Hence, the enhancement of light–matter interaction results in a higher sensitivity with respect to the external pump excitation identifying with the experimental result.

The resonance condition modulating of the MKR coated with WSe₂ by the 405-/660-nm laser pumping can be explained as follows: because of the absorption characteristic of WSe₂ at 405/660 nm, WSe₂-coated MKR is modulated by the photothermal effect and optical excitation [8]. The carriers excited by the light can transfer their energy to phonons during the relaxation process and increase the temperature of the WSe₂. The heat generated in WSe₂ is transferred to MKR, raising the temperature and changing the refractive index of the whole structure, which caused the red shift of the resonance wavelengths [44]. In addition, the concentration of electron–hole pairs in WSe₂ increases with the excitation of external light. The real and imaginary components of the refractive index of WSe₂

are modulated by the carrier density. The resonance condition is changed by the variation of the imaginary part of WSe₂ index, which would lead to an increase of the coupling loss factor of MKR [45]. Consequently, the increase of transmitted power (i.e. the decrease of ER) can be found in the resonance wavelength.

To evaluate the absorption on guiding light induced by WSe₂, simulations are performed here to fit the experimental curves in Figure 3B and C. The comparison results are shown in Figure 5, where the simulated results and experimental curves are fitting in a high degree. The experimental transmission power depicted by black curve is obtained by transforming the original data from the logarithmic coordinate to linear coordinate. The simulated fitting results depicted by red scatters are calculated from the following equation according to the coupled mode theory of a ring-waveguide system [46]:

$$|T^2| = (1 - \gamma) \frac{2\kappa_r [1 + \sin(\beta L)]}{1 + \kappa_r^2 + 2\kappa_r \sin(\beta L)} \quad (1)$$

where γ is the coupling loss caused by the light scattering on the twisted knot and the attenuation on the MKR loop; $\beta = (2\pi/\lambda)\text{Re}(n_{\text{eff}})$ is the propagation constant; λ and $\text{Re}(n_{\text{eff}})$ are resonance wavelength and real part of the mode effective index, respectively; κ_r is the coupling coefficient in connection with the round-trip fractional intensity loss. With the experimentally obtained FSR, parameter of the mode effective index $\text{Re}(n_{\text{eff}})$ is estimated with corresponding resonance wavelength. Thus, periodic minimum is achieved from (1) corresponding to a series of resonance dips, which is employed to fit the measured spectra of MKR with and without WSe₂, as described in Figure 5. The simulation result indicates the $\gamma = 0.599$, $\kappa_r = 0.007$, and $\text{Re}(n_{\text{eff}}) = 1.303363$ for the fitting transmission of the bare MKR, as well as $\gamma = 0.672$, $\kappa_r = 0.006$, and $\text{Re}(n_{\text{eff}}) = 1.373751$ for that of the MKR coated with WSe₂. The different mode effective index leads to the difference of resonance

Figure 5: Simulation based on spectra of the device.

(A) Measured normalised transmission spectra of the bare MKR (black curve) and the corresponding fitted resonance result (red circles). The fitted result is obtained by setting $\gamma = 0.599$, $\kappa = 0.007$, $n_{\text{eff}} = 1.303363$. (B) Measured normalised transmission spectra of the MKR with WSe₂ (black curve) and the corresponding fitted resonance result (red circles). The fitted result is obtained by setting $\gamma = 0.672$, $\kappa = 0.006$, $n_{\text{eff}} = 1.373751$.

wavelength in the MKR coated with and without WSe₂. Besides, the estimated coupling loss γ changes from 0.599 to 0.672, which theoretically indicates that the absorption for guiding light increases with the WSe₂ films deposited.

It follows that an experiment designed to measure the response time is performed here with the setup as shown in Figure 6A. The signal light (~1550 nm) from TLS is collected by a photo detector and transformed into electrical signal, which displays on the oscilloscope subsequently.

The external 405-/660-nm light driven by the square wave signal generator with a period (T) of ~30 ms is focused by a lens and then irradiates onto the sample in the ON or OFF state. The diameter of the 405-/660-nm laser beam size is about 1 mm, and the intensity distribution is quasi-normal. We use the translation stage to optimise the irradiation area with monitoring the optical transmitted variation. The centre position of the laser beam is aligned with the middle area of the fibre coated with WSe₂; thus,

Figure 6: Response time measurement for the device.

(A) Experimental setup for response time measuring under 405-/660-nm pump light. Response time under (B) 405-nm light with power of 41.5, 74.8, and 110.6 mW and (C) 660-nm light 48.8, 68.7, and 95.2 mW.

the overlap of the laser beam and MF is near one-third of the MKR. Figure 6B and C show the result of response time measuring in which the 405-nm pump light of 41.5, 74.8, and 110.6 mW is employed, whereas the 660-nm pump light of 48.8, 68.7, and 95.2 mW is utilised likewise. Dozens of periods of the measuring process with external pump light of a varying power all indicate a great repeatability of the device's response and recovery. The modulation depth of 1550 nm could be estimated to be ~ 7.38 dB (110.6 mW) and ~ 1.28 dB (95.2 mW) under 405- and 660-nm light, respectively. It is manifested in Figure 6B and C that the average rise and fall of response time under 405- and 660-nm light illuminating can be tuned as quick as 3.6 and 3.7 ms, respectively. Upon analyzing, the response time has little to do with the power but slightly depends on the wavelength of the incident laser. Nevertheless, the measured response time of this device might be improving through a better experiment scheme such as employing precise control over the nanosheet thickness, more homogeneous material deposition, modern nanofabrication methods, and so on.

As mentioned above, an achieved light-control-light functionality of a WSe₂-coated MKR structure is demonstrated. Table 2 sets out the property index of different types of light-control-light structure where the demonstrated device in this article appears in bold. Comparing with other kinds of structures such as MoSe₂ [47], rGO [50], and liquid crystals [52], the structure (MKR coated with WSe₂) presented in this article obtains the greatest sensitivity of ~ 0.32 dB/mW with a relatively high response speed of 3.5 ms. Consequently, provided that further optimization, such as modifying the operating wavelength and the thickness homogeneity of light-sensitive material, is carried out, the structure of MKR coated with WSe₂ is expected to be used as optical switches, multichannel fibre sensors, and amplitude modulators by virtue of high sensitivity and response speed.

Table 2: Property index of different types of light-control-light structure.

Type of structure	Q	ER	Sensitivity (dB/mW)	Response time (s)
MF + MoSe ₂ [47]	–	–	0.165	0.6
MF + graphene [48]	–	–	0.2	–
MF + TiO ₂ [49]	–	–	0.28	–
MF + rGO [50]	–	–	0.28	–
MF + bilayer graphene [51]	–	–	0.007	1×10^{-6}
MKR + liquid crystals [52]	17,111	20	0.15 at 25°C	5
MKR + graphene [41]	19,253	<5	0.02	–
MKR + WSe₂ (this article)	62,056	25.0	0.32	3.5×10^{-3}

4 Conclusion

To summarise, the resonance-enhanced all-optical power tuning and modulation functionality of MKR coated with WSe₂ structure has been demonstrated experimentally. Under 405 and 660 nm of pump laser illuminating, the modulating capacity on transmitted optical power and λ_{res} can be realised. It is manifested that a resonance with higher Q and larger ER leads to a greater sensitivity with both 405- and 660-nm light illuminating. The transmitted power variation rate reaches up to ~ 0.32 dB/mW of 405-nm laser, while yielding ~ 0.12 dB/mW of 660-nm laser. In terms of response time, the device has the fastest rise and fall time of 3.5 and 3.7 ms, respectively. In consequence, with advantages of high sensitivity, fast response speed, low cost, and compatibility for fibre network, the WSe₂-coated MKR structure has potential to be a candidate component in developing light-control functional devices.

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References

- [1] Brambilla G, Xu F, Horak P, et al. Optical fiber nanowires and microwires: fabrication and applications. *Adv Opt Photonics* 2009;1:107–61.
- [2] Tong L, Gattass RR, Ashcom JB, et al. Subwavelength-diameter silica wires for low-loss optical wave guiding. *Nature* 2003;426:816.
- [3] Jiang X, Tong L, Vienne G, et al. Demonstration of optical micro-fiber knot resonators. *Appl Phys Lett* 2006;88:223501.
- [4] Li X, Ding H. All-fiber magnetic-field sensor based on microfiber knot resonator and magnetic fluid. *Opt Lett* 2012;37:5187–9.
- [5] Lu H, Tao J, Chen L, et al. All-optical tuning of micro-resonator overlaid with MoTe₂ nanosheets. *J Lightwave Technol* 2019;37:3637–46.
- [6] Sulaiman A, Harun SW, Ahmad F, Norizan SF, Ahmad H. Electrically tunable microfiber knot resonator based erbium-doped fiber laser. *IEEE J Quantum Electron* 2012;48:443–6.
- [7] Wu Y, Zeng X, Rao Y, Gong Y, Hou C, Yang G. MOEMS accelerometer based on microfiber knot resonator. *IEEE Photonics Technol Lett* 2009;21:1547–9.
- [8] Yu S, Wu X, Wang Y, Guo X, Tong L. 2D materials for optical modulation: challenges and opportunities. *Adv Mater* 2017;29:1606128.

- [9] Zheng Z, Zhao C, Lu S, et al. Microwave and optical saturable absorption in graphene. *Opt Express* 2012;20:23201–14.
- [10] Zhao J, Liu H, Yu Z, et al. Rise of silicene: a competitive 2D material. *Prog Mater Sci* 2016;83:24–151.
- [11] Liu H, Neal AT, Zhu Z, et al. Phosphorene: an unexplored 2D semiconductor with a high hole mobility. *ACS Nano* 2014;8:4033–41.
- [12] Zhang S, Yan Z, Li Y, Chen Z, Zeng H. Atomically thin arsenene and antimonene: semimetal–semiconductor and indirect–direct band-gap transitions. *Angew Chem Int Ed* 2015;54:3112–5.
- [13] Liu M, Tang R, Luo A, et al. Graphene-decorated microfiber knot as a broadband resonator for ultrahigh-repetition-rate pulse fiber lasers. *Photon Res* 2018;6:C1–7.
- [14] Wang Y, Zhang F, Tang X, et al. All-optical phosphorene phase modulator with enhanced stability under ambient conditions. *Laser Photonics Rev* 2018;12:1800016.
- [15] Wang K, Zheng J, Huang H, et al. All-optical signal processing in few-layer bismuthene coated microfiber: towards applications in optical fiber systems. *Opt Express* 2019;27:16798–811.
- [16] Wang Y, Huang W, Zhao J, et al. A bismuthene-based multifunctional all-optical phase and intensity modulator enabled by photothermal effect. *J Mater Chem C* 2019;7:871–8.
- [17] Song Y, Chen Y, Jiang X, et al. Nonlinear few-layer antimonene-based all-optical signal processing: ultrafast optical switching and high-speed wavelength conversion. *Adv Opt Mater* 2018;6:1701287.
- [18] Wang Y, Huang W, Wang C, et al. An all-optical, actively Q-switched fiber laser by an antimonene-based optical modulator. *Laser Photonics Rev* 2019;13:1800313.
- [19] Song Y, Liang Z, Jiang X, et al. Few-layer antimonene decorated microfiber: ultra-short pulse generation and all-optical thresholding with enhanced long term stability. *2D Mater* 2017;4:045010.
- [20] Zhang Y, Lim C K, Dai Z, et al. Photonics and optoelectronics using nano-structured hybrid perovskite media and their optical cavities. *Phys Rep* 2019;798:1–51.
- [21] Song Y, Chen Y, Jiang X, et al. Nonlinear few-layer MXene-assisted all-optical wavelength conversion at telecommunication band. *Adv Opt Mater* 2019;7:1801777.
- [22] Xiang Q, Yupeng Z, Qingdong O, et al. Photonics and optoelectronics of 2D metal–halide perovskites. *Small* 2018;14:1800682.
- [23] Brixner LH. Preparation and properties of the single crystalline AB₂-type selenides and tellurides of niobium, tantalum, molybdenum and tungsten. *J Inorg Nucl Chem* 1962;24:257–63.
- [24] Li H, Huang Z, Lang Y, et al. Broadband all–light–control with WS₂ coated microfibers. *Opt Express* 2019;27:12817–31.
- [25] Nath M, Kar S, Raychaudhuri AK, Rao CNR. Superconducting NbSe₂ nanostructures. *Chem Phys Lett* 2003;368:690–5.
- [26] Wang G, Liang G, Baker MAA, et al. Nonlinear optical performance of few-layer molybdenum diselenide as a slow-saturable absorber. *Photonics Res* 2018;6:674–80.
- [27] Li H, Lu G, Wang Y, et al. Mechanical exfoliation and characterization of single-and few-layer nanosheets of WSe₂, TaS₂, and TaSe₂. *Small* 2013;9:1974–81.
- [28] Podzorov V, Gershenson ME, Kloc C, Zeis R, Bucher E. High-mobility field-effect transistors based on transition metal dichalcogenides. *Appl Phys Lett* 2004;84:3301–3.
- [29] Chiritescu C, Cahill DG, Nguyen N, et al. Ultralow thermal conductivity in disordered, layered WSe₂ crystals. *Science* 2007;315:351–3.
- [30] Upadhyayula LC, Loferski JJ, Wold A, Girit W, Kershaw R. Semiconducting properties of single crystals of n- and p-type tungsten diselenide (WSe₂). *Appl Phys* 1968;39:4736–40.
- [31] Huang J, Pu J, Hsu C, et al. Large-area synthesis of highly crystalline WSe₂ monolayers and device applications. *ACS Nano* 2013;8:923–30.
- [32] Huang C, Wu S, Sanchez AM, et al. Lateral heterojunctions within monolayer MoSe₂–WSe₂ semiconductors. *Nat Mater* 2014;13:1096.
- [33] Li M, Shi Y, Cheng C, et al. Epitaxial growth of a monolayer WSe₂–MoS₂ lateral pn junction with an atomically sharp interface. *Science* 2015;349:524–8.
- [34] Fang H, Chuang S, Chang TC, Takei K, Takahashi T, Javey A. High-performance single layered WSe₂ p-FETs with chemically doped contacts. *Nano Lett* 2012;12:3788–92.
- [35] Chuang H, Tan X, Ghimire NJ, et al. High mobility WSe₂ p- and n-type field-effect transistors contacted by highly doped graphene for low-resistance contacts. *Nano Lett* 2014;14:3594–601.
- [36] Tonndorf P, Schmidt R, Bottger P, et al. Photoluminescence emission and Raman response of MoS₂, MoSe₂, and WSe₂ nanolayers. *Opt Express* 2013;21:4908.
- [37] Luo X, Zhao Y, Zhang J, et al. Effects of lower symmetry and dimensionality on Raman spectra in two-dimensional WSe₂. *Phys Rev B* 2013;88:293–8.
- [38] Liu W, Kang J, Sarkar D, Khatami Y, Jena D, Banerjee K. Role of metal contacts in designing high-performance monolayer n-type WSe₂ field effect transistors. *Nano Lett* 2013;13:1983–90.
- [39] Si K, Huang Y, Zhao Q, et al. Terahertz surface emission from layered semiconductor WSe₂. *Appl Surf Sci* 2018;448:416–23.
- [40] Lim KS, Jasim AA, Damanhuri SSA, Harun SW, Rahman BMA, Ahmad H. Resonance condition of a microfiber knot resonator immersed in liquids. *Appl Optics* 2011;50:5912–6.
- [41] Meng Y, Deng L, Liu Z, et al. All-optical tunable microfiber knot resonator with graphene-assisted sandwich structure. *Opt Express* 2017;25:18451–61.
- [42] Lu H, Wang Z, Huang Z, et al. Resonance-assisted light–control–light characteristics of SnS₂ on a microfiber knot resonator with fast response. *Photonics Res* 2018;6:1137–43.
- [43] Guan H, Xia K, Chen C, et al. Tungsten disulfide wrapped on micro fiber for enhanced humidity sensing. *Opt Mater Express* 2017;7:1686–96.
- [44] Sun Q, Sun X, Jia W, et al. Graphene-assisted microfiber for optical-power-based temperature sensor. *IEEE Photonic Tech L* 2016;28:383–6.
- [45] Stetsenko MO, Voznyi AA, Kosyak VV, et al. Plasmonic effects in tin disulfide nanostructured thin films obtained by the close-spaced vacuum sublimation. *Plasmonics* 2016;12:1213–20.
- [46] Stokes LF, Chodorow M, Shaw HJ. All-single-mode fiber resonator. *Opt Lett* 1982;7:288–90.
- [47] Zhang D, Guan H, Lu H, et al. All light–control–light properties of molybdenum diselenide (MoSe₂)–coated-microfiber. *Opt Express* 2017;25:28536–46.
- [48] Chen J, Zheng B, Shao G, et al. An all-optical modulator based on a stereo graphene–microfiber structure. *Light Sci Appl* 2015;4:e360.

- [49] He D, Yang H, Tao J, et al. Micro fiber with cladding of titanium dioxide (TiO₂) nanoparticles and its violet light sensing. *Opt Mater Express* 2017;7:264–72.
- [50] Li D, Chen Z, Chen G, et al. Reduced graphene oxide wrapped on microfiber and its light–control–light characteristics. *Opt Express* 2017;25:5415–25.
- [51] Liu Z, Feng M, Jiang W, et al. Broadband all-optical modulation using a graphene-covered-microfiber. *Laser Phys Lett* 2013;10:065901.
- [52] Chen Z, Hsiao VKS, Li X, Li Z, Yu J, Zhang J. Optically tunable microfiber-knot resonator. *Opt Express* 2011;19:14217–22.