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High Light Tuning Efficiency in All Optical In_2Se_3 Coated Micro Knot Resonator Structure

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ABSTRACT In this paper, we demonstrate high light tuning efficiency in indium selenide (In_2Se_3) coated micro knot resonator (MKR). Tuning of output optical power is realized via externally pump light excitation at wavelengths of 405, 532 and 660 nm. High light tuning efficiency is achieved with improved coating method, enhanced light-matter interaction, strong absorption of In_2Se_3 and highly sensitive to change of the coupling condition. The tuning efficiency of the output optical power is up to 0.815 dB/mW. The temporal response of the structure is around 1.6 ms under 532-nm pump light excitation. The sensitivity depends on micro knot resonator resonance including Q factor and ER. The MKR tuning performance with various diameters of the resonator and the diameter of the microfiber is investigated. The advantages of this device are easy fabrication, all-optical tuning, high sensitivity and fast response. This proposed structure might find potential applications in all-fiber-optic based tunable devices such as optical modulator, detector, etc.

INDEX TERMS Two dimensional material, indium selenide, light tuning, micro knot resonator.

I. INTRODUCTION

Building all-fiber photonic devices yield plenty of advantages such as compatibility with the fiber communication network, low cost and low optical losses [1], [2] etc. The passive fiber based optical components such as isolators, circulators and amplifiers are mature technologies [3], [4]. However, active tunable fiber based optical components are still an ongoing research domain [5], [6]. In this paper, we report a tunable light controlled light fiber based optical component with indium selenide (In_2Se_3) coated micro knot resonator (MKR).

In_2Se_3 nanosheet is layered semiconductor, belonging to group III-VI family with direct bandgap. Large-scale growth of 2D In_2Se_3 nanosheet has been reported in ref. [7], [8]. It finds applications in such as phase change memory [9], [10], photovoltaic [11], [12], photo-detection [13]–[15] and strain sensors [8] etc. For photovoltaic applications, it acts as an absorber layer in solar cell devices [11]. For photo-detection, it forms a reverse-biased Schottky barrier yielding high performance devices of external quantum efficiency approaching 866% and the dark current in the picoamp range [13]. Though it has been investigated in many of the above-mentioned applications, the light tuning properties with MKR has not been reported in the literature yet.

An MKR is an interlaced tapered fiber [16] of several micron-meters in diameter that is knotted in order to form a ring of several hundred micron-meters in diameters [17], [18]. When the optical path length satisfies an integer number of 2π, it forms resonances which yield light confinement boosting light-matter interaction. It finds applications in such as seawater temperature sensor [19], wavelength switchable vortex beam generation [20] and all-optical tunable devices [21] etc.

Tuning of MKR and microfiber (MF) devices has been achieved with various materials such as liquid crystal, polymer, lithium niobite, and 2D materials. All-optical tunable

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MKR with graphene-assisted sandwich structure has been reported [22]. In order to achieve high tuning efficiency of the MKR, the transition metal dichalcogenides (TMDs) including tungsten disulfide (WS_2) [23], tin disulfide (SnS_2) [24], Molybdenum telluride ($MoTe_2$) [25] has been applied.

An active optical component by indium selenide coated micro-knot resonators (ISMKR) structure is investigated here where the tuning of output optical power is realized via externally pump light excitation. The advantages of this device are easy fabrication, all-optical tuning, high sensitivity and fast response. The high sensitivity of light tuning of the ISMKR is achieved with improved coating method, enhanced light-matter interaction, strong absorption of In_2Se_3 and highly sensitive to change of the coupling condition. The dependence of sensitivity on MKR resonance (Q factor and ER) is investigated. In addition, the MKR tuning performance with various diameters of the resonator (d_r) and the diameter of the microfiber (d_M) is also investigated. This paper is structured as follows: the next section will present the structure fabrication. The tuning properties with different external pump light wavelengths at different power will be described in the following section. The last section will be some discussions on the presented results.

II. STRUCTURE FABRICATION

The ISMKR structure fabrication consists of tapering the fiber, interlacing the micro-fiber into an MKR and then the coating of IS onto MKR. Tapering fiber begins with a standard SMF-28 fiber and it is fabricated by a heat-flame taper-drawing method [16]. The two ends of the tapered fiber are then interlaced together to form a knotted structure as shown in the microscopic image of Fig. 1(a). It can be seen from Fig. 1(a) that the diameter of the micro-fiber is around 7.81 μm and the MKR loop have a diameter of around 662 μm.

The micro-fiber of several micron-meters in diameter yields a good compromise between output light power and the portion of evanescent light that leaks out facilitating light-matter interaction. Optical characterization of the bare MKR is performed by shining a tunable laser source (TLS: ANDO, AQ4321D) into the fiber and the output spectrum is recorded by an optical spectrum analyzer (OSA: YOKOGAWA, AQ6317C). One of the spectra ranging from 1555.35 nm to 1559.20 nm is shown in Fig. 1(b) where the largest ER extinction ratio (ER) is round 17.98 dB which obtains near the resonance wavelength of 1557.9 nm. The free spectral range (FSR) of the spectrum is around 0.85 nm, from which we can deduce that the effective refractive index of the resonance mode near 1550 nm is around 1.49 (estimated from coupled-mode theoretical fitting [26]).

The last step of ISMKR fabrication is coating the IS nanosheet onto the MKR. The UV-VIS absorption spectrum of the commercially available IS nanosheet dispersion is characterized as shown in Fig. 2, where the absorption strength decreases with the increase of the excitation wavelength.

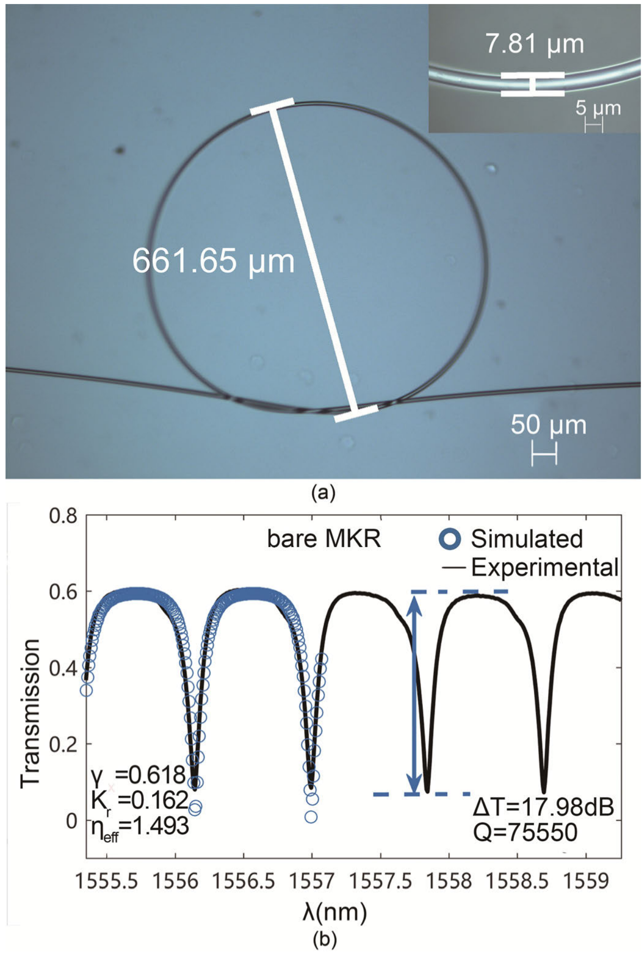

FIGURE 1. (a) Microscopic image of the MKR with a loop diameter of about 661.65 μm and the inset is a microscopic image of MF where the diameter is about 7.81 μm. (b) Experimental measurement (solid black line) of the transmission of the bare MKR. The largest ER is round 17.98 dB which obtains near the resonance wavelength of 1557.9 nm. Blue circled line corresponds to numerically fitted curves where the estimated coupling loss is 0.618, coupling efficiency is around 0.162 and the mode effective index is around 1.493.

The In_2Se_3 nanosheets have a concentration of 1mg/ml, while the thickness varies from one till ten layers.

The coating of IS onto the MKR is performed by simple dip-drop method. In order to facilitate the coating process, a basin made of the UV glue is constructed surrounding the MKR as schematically shown in Fig. 3. The input and output of the fiber are connected with a TLS and power meters respectively monitoring the real-time output power. The transfer of IS nanosheet is realized by a pipette onto one third of the MKR circumferences. The deposition is finished after three hours' evaporation of the solvent which is indicated by the stable output power. The scanning electron microscope (SEM) characterization of the as-fabricated ISMKR structure is performed after the tuning experiment and the results are shown in Fig. 4. It shows that the micro-fiber is about 7.81 μm in diameter and the averaged thickness is around 359 nm. There are areas show less coverage of the In_2Se_3 nanosheets on the MF and nonuniformity. This can be

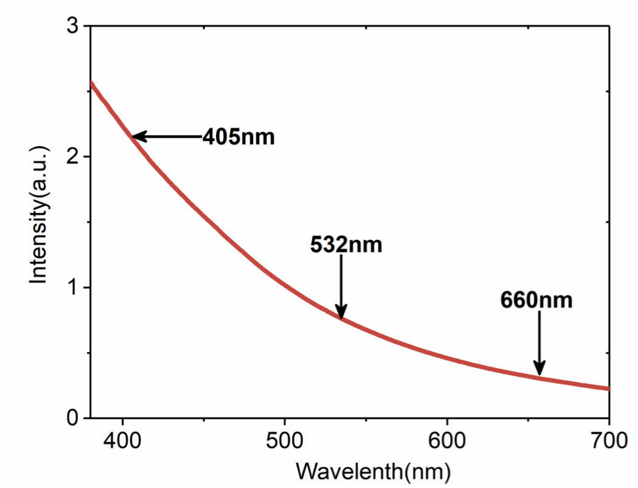

FIGURE 2. Absorption spectrum of In_2Se_3 nanosheets.

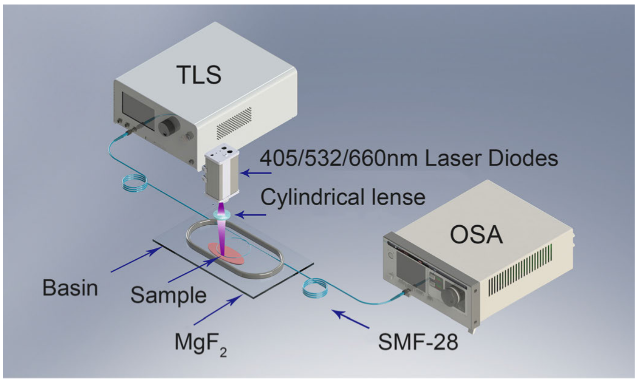

FIGURE 3. Experimental setup for the all optical transmitted light power tuning by different violet/green/red pump light powers.

improved with optimization of the deposition technology and tapering fiber process.

III. ALL OPTICAL TUNING EXPERIMENTS

The experimental setup is shown in Fig. 3 where the samples under test are either bare MKR or ISMKR structure. The TLS ranging from 1520 nm to 1620 nm is employed as the laser source. The output is collected by an OSA in order to record the output spectrum of the sample under test. The pump light of different wavelengths (405, 532 and 660 nm) at different power (up to around 40 mW) as described in Table 1 externally pump on top of the sample via a cylindrical lens.

The light tuning experiment result of bare MKR at 405 nm of different powers is shown in Fig. 5 (a) from which one can find little noticeable variation of the output power. Other pump light tuning experiments of the bare MKR yield similar results and there is hardly variation in the output spectrum. The maximum power variations are only 0.3 dB, 0.3 dB and 0.4 dB with different pump light powers at the pump light wavelength of 405 nm, 532 nm and 660 nm respectively. These experimental results of the bare MKR show that there is no light tuning effect if there is no functional material that interacts with the evanescent light leaking out of the micro-fiber.

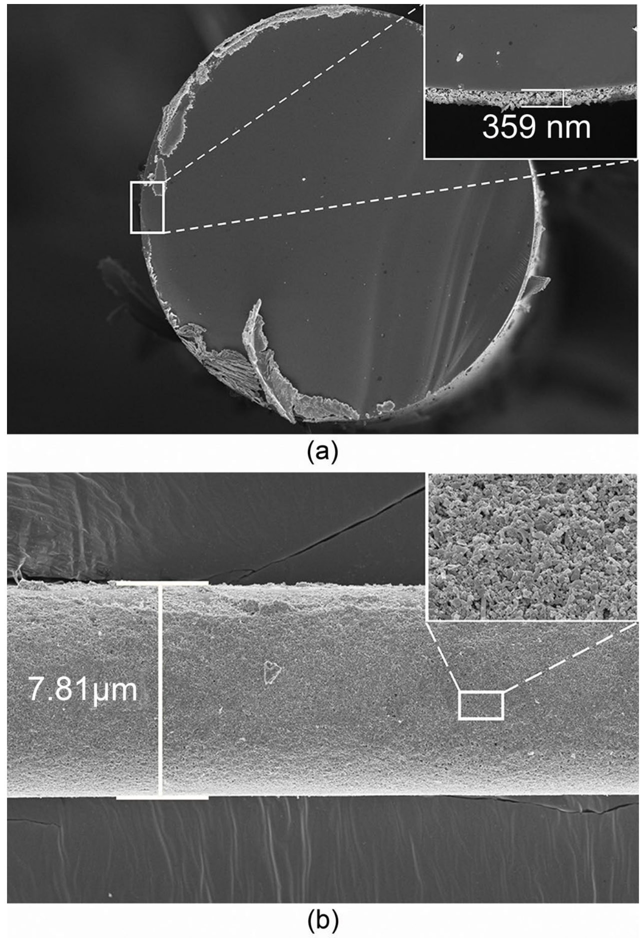

FIGURE 4. SEM images of a small part in the MKR coated with In_2Se_3 nanosheets (a) which shows the MF of about 7.81 μm in diameter and the inset shows an enlarged view of the coated material. (b) which shows a cross-section view of the MF with In_2Se_3 nanosheets and the inset shows the coated In_2Se_3 thickness is around 359 nm.

TABLE 1. Light tuning experiment with different pump light wavelength of different pump powers at the resonance wavelength around 1584.64 nm.

Pump light wavelength	Pump power(mW)	Maximum output variation of ISMKR (dB)
405 nm	0, 8.9, 16.6, 19.5, 27.6	22.5
532 nm	0, 5.0, 16.6, 27.7, 32.0	13.07
660 nm	0, 2.1, 14.2, 24.8, 39.5	14.39

Similar experiments of the same pump light wavelengths and the same variation of the pump light powers (as indicated in the first two columns of Table 1) are performed on the ISMKR structure. The results are shown in Fig. 5(b-d) respectively. Qualitatively one finds large variations of the output power and the maximum power variation are of 22.5, 13.07 and 14.39 dB under 405 nm, 532 nm and 660 nm pump light excitation respectively as indicated in the last column of Table 1.

Thanks to the presence of IS nanosheet, light tuning functionality can be achieved. Quantitatively, the power variation rate (termed as sensitivity S here) at different probe light wavelengths (1584.64, 1588.93 and 1595.78 nm) under

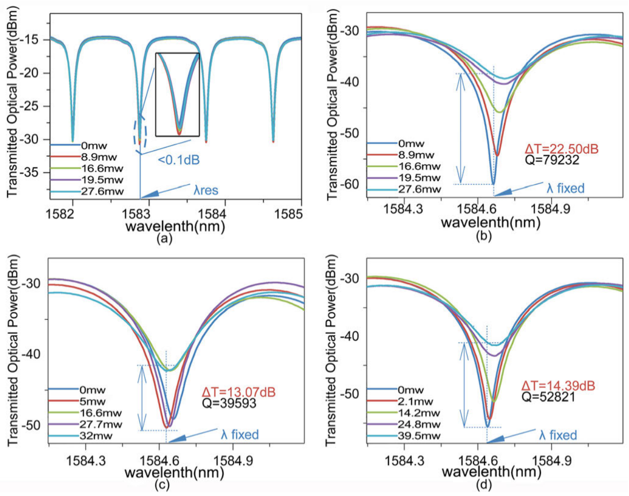

FIGURE 5. (a) The blue, red, green, purple and light blue coloured curves correspond to the transmission with external violet (405 nm) pump power of 0, 8.9, 16.6, 19.5 and 27.6 mW of the bare MKR. (b) Transmission of the In_2Se_3 coated MKR structure at different external violet pump light power excitation at the resonance wavelength around 1584.64 nm. The blue, red, green, purple and light blue coloured curves correspond to the transmission with external violet pump power of 0, 8.9, 16.6, 19.5 and 27.6 mW. (c) Transmission of the MKR with In_2Se_3 structure at different external green pump light power excitation at the resonance wavelength around 1584.64 nm. The blue, red, green, purple and light blue coloured curves correspond to the transmission with external green pump power of 0, 5, 16.6, 27.7 and 32 mW. (d) Transmission of the MKR with In_2Se_3 structure at different external red pump light power excitation at the resonance wavelength around 1584.64nm. The blue, red, green, purple and light blue coloured curves correspond to the transmission with external red pump power of 0, 2.1, 14.2, 24.8 and 39.5mW.

different pump light conditions are linearly fitted and the results are shown in Fig. 6. Table 2 summarizes the power variation rate (S) at different probe light wavelengths under different pump light excitation. The sensitivity is affected both by the resonance property at the probe light wavelength and the absorption property of the two-dimensional material at the pump light wavelength. Linear fit of sensitivities versus resonance Q and ER under 405 nm, 532 nm and 660 nm light at the selected wavelengths are shown in Fig. 7 a and b respectively. A large Q, high ER resonance, weak absorption at the probe light and a strong absorption property at the pump light wavelength yield a higher sensitivity.

The largest power variation rate is 0.811 dB/mW which is obtained under 405 nm pump light excitation at the probe light wavelength of 1584.64 nm (Fig. 5(b)) and its linearity is around 0.907 (blue curve in Fig. 6(a)). From Table 2, one can see that for a fixed probe light wavelength, the sensitivity is tend to be larger for short pump light wavelength which is consistent with the UV-VIS spectrum shown in Fig. 2. The largest sensitivity is obtained at probe light wavelength of 1584.64 nm for the three different pump light wavelengths and they are 0.313 dB/mW and 0.338 dB/mW respectively for 532 and 660 nm pump light. Other S values for the probe light wavelength of 1588.93 nm are 0.548, 0.146 and 0.126 dB/mW which is achieved under 405, 532 and 660 nm pump light excitation respectively. The S value at the probe light wavelength of 1595.78 nm are 0.377, 0.216 and 0.129 dB/mW which is achieved under 405, 532 and 660 nm pump light excitation respectively. The tuning performance is related to d_r and d_M. We fabricated several ISMKRs with different d_r and d_M. As shown in Fig. 8, the sensitivity is different for various d_r and d_M. The highest sensitivity is obtained when dr is 662 μm and dM is 7.81 μm for the 405, 532 and 660 nm laser, as shown in Fig. 8(a)-(c), respectively.

In order to characterize the temporal response of the ISMKR structure, experiments are carried at different pump light powers of the three different pump light sources. The experimental setup is shown in Fig. 9 where the pump light is controlled by a signal generator with a square wave of 20 ms in period and the duty cycle is of 1/2. The output is collected by a photo detector connected to an oscilloscope. Fig.10 shows the time response under 405, 532 and 660 nm pump light excitation of different powers respectively. The rise and fall time have little difference between different pump light conditions. The fastest rise/fall time is around 1.6/1.6 ms.

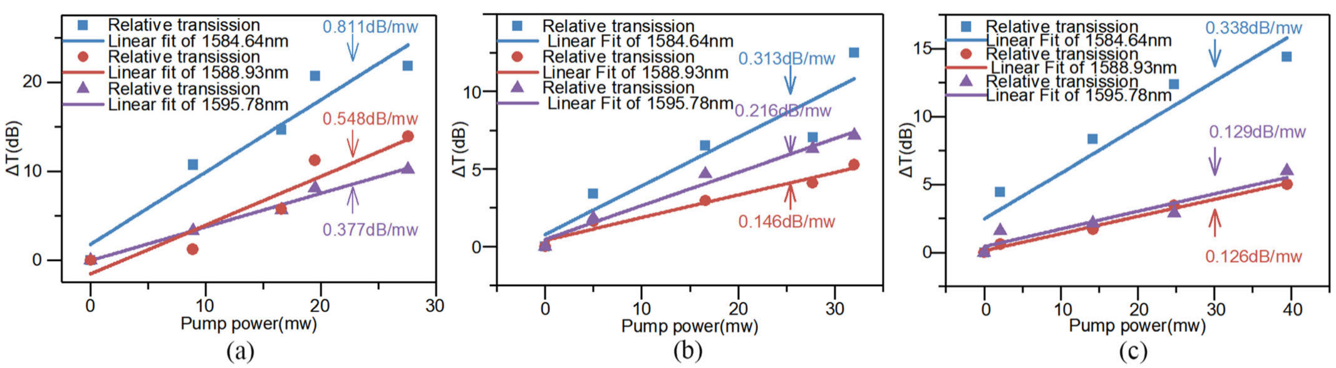

FIGURE 6. (a) Linear fit of ΔT versus different signal light wavelengths under external violet pump light power excitation. The blue curve corresponds to signal light at 1584.64 nm, the red curve corresponds to signal light at 1588.93 nm while the purple curve corresponds to signal light at 1595.78 nm. (b) Linear fit of ΔT versus different signal light wavelengths under external green pump light power excitation. The blue curve corresponds to signal light at 1584.64 nm, the red curve corresponds to signal light at 1588.93 nm while the purple curve corresponds to signal light at 1595.78 nm. (c) Linear fit of ΔT versus different signal light wavelengths under external red pump light power excitation. The blue curve corresponds to signal light at 1584.64 nm, the red curve corresponds to signal light at 1588.93 nm while the purple curve corresponds to signal light at 1595.78 nm.

TABLE 2. **ΔTmax and sensitivity (S) obtained at different probe light wavelength.**

Pump light wavelength / λres(nm)	405nm		532nm		660nm	
	ΔTmax	S	ΔTmax	S	ΔTmax	S
1584.64	22.50	0.811	13.07	0.313	14.39	0.338
1588.93	13.89	0.548	5.27	0.146	5.02	0.126
1595.78	10.90	0.377	7.18	0.216	6.01	0.129

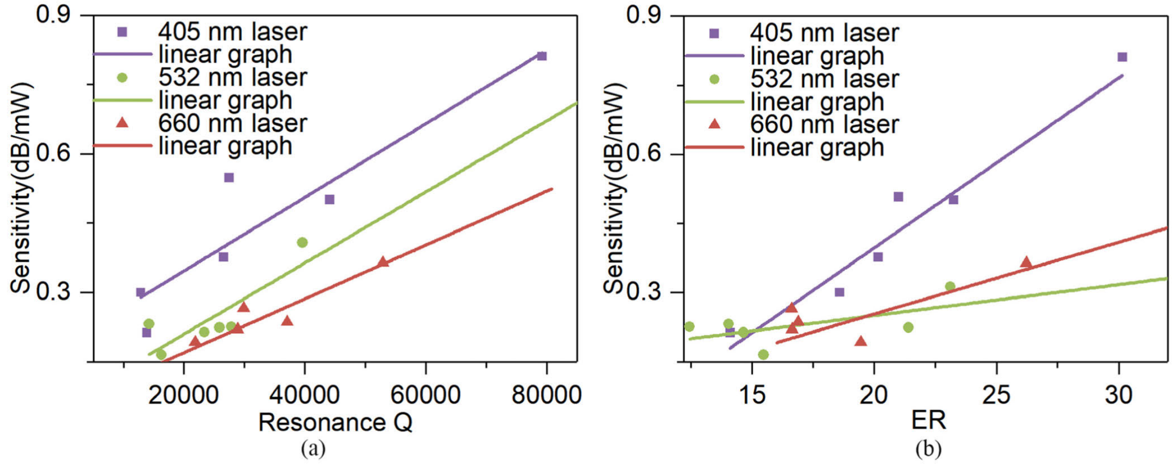

FIGURE 7. **(a) resonance Q and (b) ER for the selected resonance positions at λres =∼ 1583.71 nm, λres =∼ 1584.64 nm, λres =∼ 1588.05 nm, λres =∼ 1588.93 nm, λres =∼ 1594.92 nm, λres =∼ 1595.78 nm.**

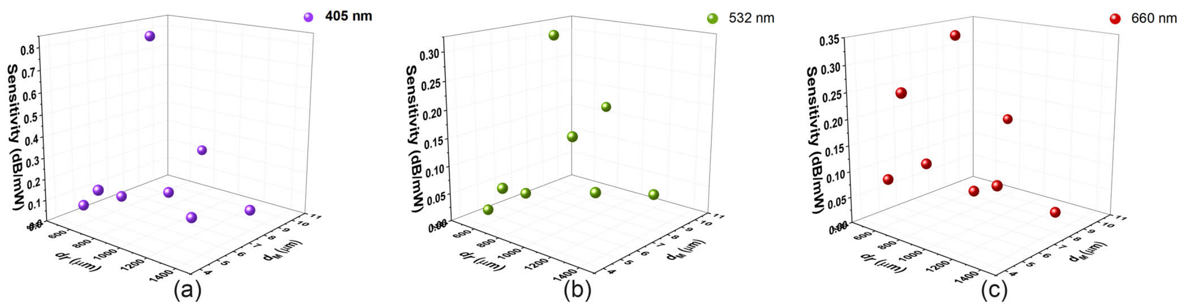

FIGURE 8. **Experimental results on sensitivity with different d_r and d_M for the (a) 405 nm, (b) 532 nm and (c) 660 nm laser.**

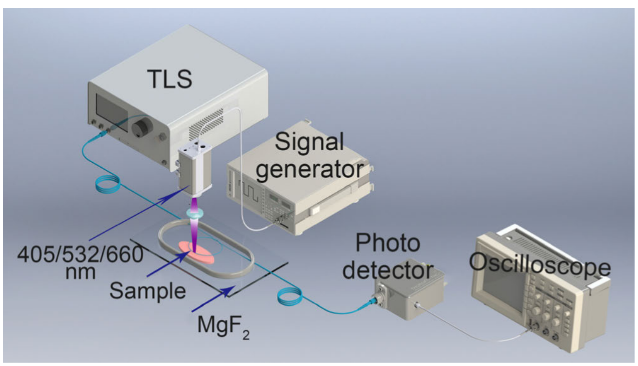

FIGURE 9. **Experimental setup for measuring the time response of ISMKR structure transmitted light power tuning by different violet/green/red pump light powers.**

A possible mechanism of the high tuning efficiency (0.815 dB/mW) and moderate temporal response (1.6 ms) might be as follows: The strong absorption property of the In_2Se_3 at the pump light wavelength lead to local heating effect [27], raising the temperature and changing the refractive index of the fiber. The heat generated in the 2D material In_2Se_3 under pump laser is diffused into the MF and the temperature of the MF is increased, resulting in an evident index change of the fiber [27]. In our previous works, we measured the temperature variation of MF coated with WSe_2 under the irradiation of the 405, 532 and 660 nm pump lasers. The temperature variation gives sensitivities of 0.4°C/mW for increasing and decreasing the pump power [28].

Whereas, weak light absorption at probe light (signal light) combining with resonances of high light confinement, high Q factor and steep resonance slope enables the property of highly sensitive to change of the coupling condition. When the local temperature of the nanosheets changes, it leads to a change in the coupling condition of the MKR. Therefore, one can experimentally observe the variation of the resonance ER. Since the dominating effect is the thermo-optic effect

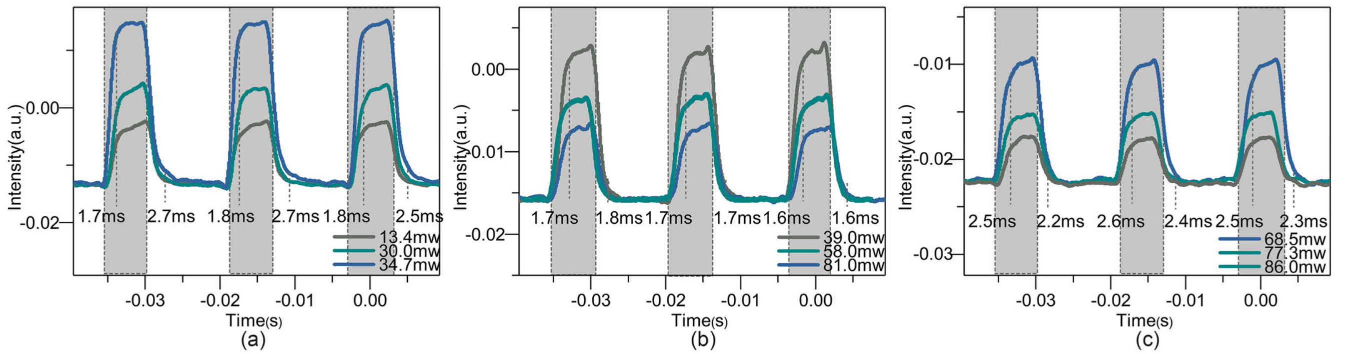

FIGURE 10. (a) Response time measured under the violet power of 13.4, 30 and 34.7 mW excitation. (b) Response time under the green power of 39, 58 and 81 mW excitation. (c) Response time under the red power of 68.5, 77.3 and 86 mW excitation.

TABLE 3. Performances comparison of different light-control-light structures.

Type of structure	Sensitivity(dB/mW)	Response time
MF with $MoSe_2$ [31]	0.165	0.6 s
MF with TiO_2 [32]	0.280	-
MKR with graphene [33]	0.150	-
Side-polished fiber with liquid crystals [29]	0.150 at 25°C	5 s
MKR with WSe_2 [30]	0.320	3.5 ms
In_2Se_3 + MKR (this paper)	0.815	1.6 ms

and the long deposition length of around 300 μm, the temporal response time is moderate one around 1.6 ms. The time response can be improved if more advanced fabrication technique such as monolayer nanosheet wet transferring and lithography defined shorter deposition length [1] etc.

Regarding to sensitivity enhancement of the ΔT variation with respect to pump light excitation in ISMKR, the bare MKR has a ΔT of less than 0.3 dB under 27.6 mW violet pump light excitation whereas the MKR with In_2Se_3 yields a ΔT of 22.5 dB. As a consequence, the MKR with In_2Se_3 has over 75 fold enhancement in the ΔT variation rate.

Table 3 shows the performances of different types of light-control-light structures. In terms of sensitivity, the MKR with In_2Se_3 demonstrated in this paper (bold font in Table 3) outperforms other configurations. Whereas, the response time of MKR with In_2Se_3 yields a better result than those structures such as liquid crystals [29] and WSe_2 [30]. Several factors contribute to the high sensitivity and fast response time. Firstly, we have improved the nanosheets coating method. The In_2Se_3 is coated on one third of the MKR and nanosheets are coated away from the knot of the ring. Secondly, the light-matter interaction is enhanced with optimized dimension of MKR, uniformity of MF, diameter of MF, the transition part of MF. Thirdly, In_2Se_3 provides strong absorption in the visible light. Fourthly, weak light absorption at probe light (signal light) combining with resonances of high light confinement, high Q factor and steep resonance slope enable the property of highly sensitive to change of the coupling condition.

IV. CONCLUSION

We demonstrated experimentally a low-cost, all-optical highly tuning efficiencies ISMKR structure. The MF diameter is of 7.81μm and the diameter of the MKR loop is around 661.65 μm. The deposition length of the MKR is around one third of the ring which is around 300 μm. The tuning efficiency yields up to 0.815 dB/mW which is obtained at 405 nm pump light excitation. The temporal response of the structure is around 1.6 ms. The temporal response can be improved with optimized thickness of In_2Se_3 nanosheets, the deposition fiber length and more homogeneous nanosheet deposition. The structure presented here can find applications in all-optical modulator, all-optical circuitry, visible light detector, sensors and multi-dimensionally tunable optical devices, etc.

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(Luqi Luo and Yunyao Ou contributed equally to this work.)

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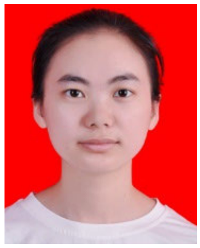

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