Enhanced Stimulated Brillouin Scattering Effect by Using Multilayer Molybdenum Disulfide on Fibre End

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***Abstract*—For the first time we observe that SBS gain can be enhanced by 1.5 dB with multilayer MoS_2 on fibre end. The SBS gain enhancement is observed within 200-MHz range, indicating the broadband Brillouin scattering characteristics of MoS_2.**

***Keywords*—multilayer MoS_2; SBS gain enhancement; broadband Brillouin scattering characteristics**

I. INTRODUCTION

Stimulated Brillouin scattering (SBS) can be regarded as the coherent scattering process between photon and phonon in materials, which can be found many applications such as microwave frequency generation and processing, selective signal amplifications, slow light and sensors. Especially in the microwave photonics, microwave frequency generation and microwave photon filter based on stimulated Brillouin scattering attract many attentions. Thus, different kinds of methods to enhance SBS gain are desired. Among these methods, using fibre with new materials is a novel one. To reduce the physical size, materials with high SBS gain efficiency is desired. Chalcogenide fibre or waveguide [1], [2] has been considered as good choice for SBS applications with small size (centimetres dimension) due to its high SBS gain efficiency. Recent years, as an element of the chalcogenide family, molybdenum disulfide (MoS_2) has been widely studied due to its excellent photoelectric properties, and the thickness of monolayer MoS_2 is only about 1 nm. Some researches about the third-harmonic generation [3] and the Kerr nonlinearity enhancement [4] of MoS_2 have already been discussed. But, so far, we have not found the SBS study of MoS_2. Thus, to investigate the Brillouin scattering characteristics, we transfer MoS_2 with different thickness from 2 layers to about 48 layers onto the fibre end by performing a directly-contact transfer method with polydimethylsiloxane (PDMS), and conduct an experiment to study whether MoS_2 could contribute to Brillouin scattering effect. Surprisingly, we observe that the SBS gain is increased with MoS_2 on fibre end, and the SBS gain enhancement is increased as the thickness of the transferred MoS_2. The SBS gain is increased by 1.5 dB using the thickest MoS_2 sample with 48 layers. Besides, we observe the similar SBS gain enhancement by shifting the Brillouin frequency shift of 200 MHz using another fibre type, indicating the broadband Brillouin scattering characteristics of MoS_2. If MoS_2 can be transferred onto tap fibre or waveguide to enhance the light-matter interaction, the MoS_2-based device can be a good candidate for versatile novel application of microwave photonics.

II. FABRICATION

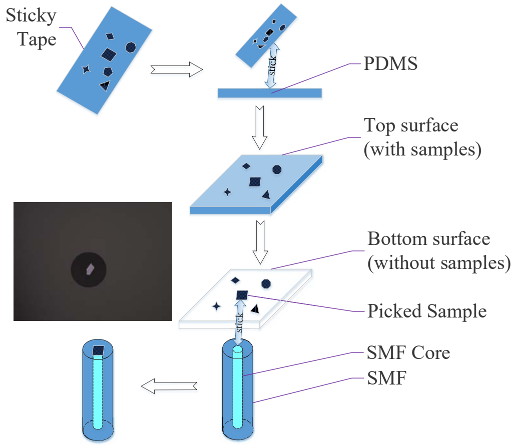

Fig. 1. The fabrication sketch: directly-contact method based on PDMS.

Fig. 1 shows the sequential fabrication sketch of MoS_2 transferred onto fibre end. Firstly, we apply the traditional mechanical exfoliation method to rip the tape on which there are some MoS_2 samples. After achieving some relatively thin MoS_2 samples, we stick the tape with those samples onto the solidified PDMS, and put it down motionlessly for about ten minutes. Then, a piece of PDMS with the MoS_2 samples can be obtained, and we can locate the specific MoS_2 sample by using an optical microscope. Finally, the top of the single-mode fiber (SMF) core is completely covered by the picked MoS_2 sample sticked on the top surface of PDMS via micro-manipulation under a precisely controlled 3-dimension moving stage, as shown by the inserted photo in Fig. 1. During the entire transfer process, the picked sample can be attached well to the fibre end without the cumbersome heating process which has been widely used in the previous work.

Fig. 2 shows the measured Raman spectrum of the thickest transferred MoS_2 on the fibre end, which clearly shows that the E^1_{2g} peak and the A^1_{2g} peak are located at about 383 cm^{-1} and 409 cm^{-1} respectively.

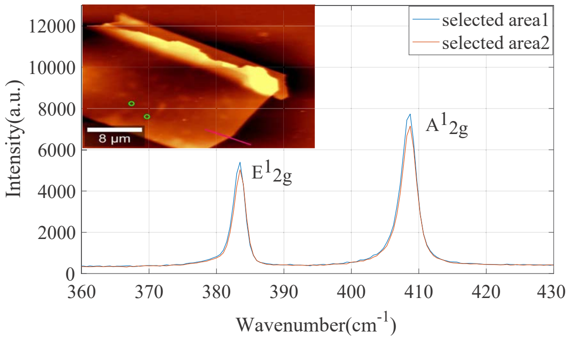

Fig. 2. The Raman spectrum of two randomly selected spots (green) on the transferred MoS_2.

The wavenumber difference between the two peaks implies the multilayer property of the transferred MoS_2. Besides, it also can be clearly seen that the Raman spectrum traces of two randomly selected areas are almost overlapped, which implies the well-distribution of the transferred MoS_2 covering the SMF core.

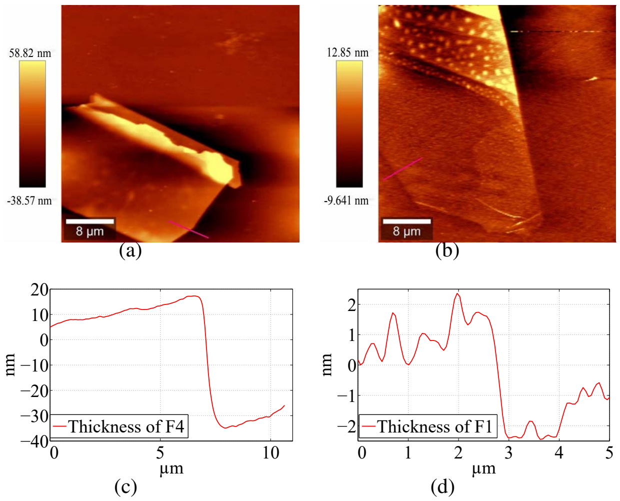

Fig. 3. Atomic force microscopy (AFM) image and the thickness of transferred MoS_2. (a) The AFM image of sample F4. (b) The AFM image of sample F1. (c) The thickness measurement of F4. (d) The thickness measurement of F1.

In order to know the number of atomic layers of the transferred MoS_2 precisely, we perform the atomic force microscopy (AFM) measurement for different transferred MoS_2 samples, as shown in Fig. 3. According to the single-layer thickness standard definition and the consideration of the instrument error scope, the thickness of monolayer MoS_2 is about 1nm, so we can calculate that the thickness of the thickest one F4 and the thinnest one F1 are about 48 layers and 2 layers respectively. We will use these MoS_2 samples for the following SBS measurement.

III. EXPERIMENT AND RESULTS

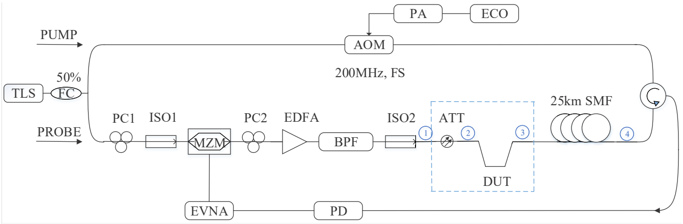

Fig. 4. Experimental setup.

Fig. 4 shows the experimental setup. A tunable laser source operating at 1550.58 nm is split into two branches by a 50% fiber coupler. In the probe branch, a sweeping signal covering the frequency from 6GHz to 12GHz can be produced by using an electrical vector network analyzer (EVNA), and it is modulated subsequently on the light to generate two sidebands by a Mach-Zehnder modulation (MZM). Then, it is sent into an erbium doped fiber amplifier (EDFA) for amplification. After that, an optical bandpass filter (BPF) removes the left sideband to ensure the stability of the SBS gain measurement. In order to remove the influence of different link losses due to the difference in material thickness during the measurement process, we add an attenuator before the MoS_2-transferred fibre (device under test, DUT). Considering the attenuator and the DUT as an entire link section, we control the loss of this link section so that it always remains the same in each measurement. Because only a few nm-thick MoS_2 is too thin to observe the SBS effect by itself, we place 25-km singal-mode fiber between the front part of DUT and the pump to measure the SBS gain variation with and without MoS_2. In the pump branch, to remove the possible SBS gain contribution from the pump reflection caused by the material, we utilize an acousto-optical modulator (AOM) with 200 MHz frequency shift driven by an electrical crystal osillation (ECO) to differentiate the pump wavelength and the carrier wavelength of the probe branch. At the end, the probe signal after the SBS process is detected by a photodiode (PD) and sent into the EVNA for SBS gain spectrum measurement.

Throughout the measurement process, we carefully consider all the possible problems that could lead to test deviation: loss, polarization and pump power. Firstly, we eliminate the effect of loss in the experiment by keeping the loss of the entire link section described before to be constant. Secondly, since the SBS gain is closely related to the polarization state, we always adjust the polarization state of the signal using the polarization controller (PC2) in each measurement so that the observed SBS gain can reach the maximum everytime. Thirdly, since the 25-km SMF is utilized here, contributing the main SBS gain in the system, we ensure that the probe and the pump power, (marked by③,④) both injecting into the 25-km SMF are constant so as to only compare the SBS gain difference brought by the transferred MoS_2 with different thickness.

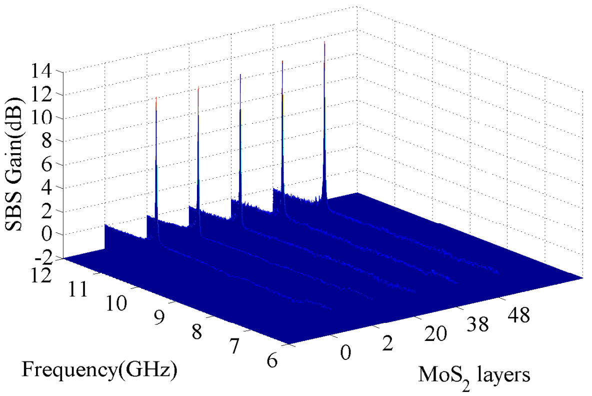

Fig. 5. SBS gain spectrum measurement for MoS_2 samples with different layers.

After excluding all the potential problems, we get the experimental result as shown in Fig. 5. There is indeed an enhancement of SBS gain by using multilayer MoS_2 with 2.26 dBm pump power. In the case of maintaining the other variables unchanged, the SBS gain increases as the thickness of the transferred MoS_2. The strongest enhancement deriving from the thickest DUT can reach 1.5 dB, and the weakest one from the thinnest DUT is almost equal to zero. In addition, we also study whether the MoS_2 has contribution on SBS gain at another Brillouin frequency shift. As a result, shown in Table I, utilizing the pure silica fibre with 200 MHz higher Brillouin frequency shift than the SMF, MoS_2 still shows SBS gain enhancement, while its value is slightly reduced. The experimental results probably indicate that the Brillouin scattering bandwidth of MoS_2 is higher than 200 MHz.

TABLE I
ENHANCED SBS GAIN FOR DIFFERENT FIBER TYPE

Fiber Type	**SBS frequency shift**	**SBS gain enhancement**
SiO_2	10.8GHz	1.50dB
Pure Silica	11 GHz	1.20dB

Finally, to observe the effect of MoS_2 on SBS gain under different pump power, the thickest DUT and pure silica fibre are selected for SBS gain experiment. The loss of pure silica fiber is much higher than the SMF so that we could protect the MoS_2 from being damaged by too high power. As shown in Fig. 6, with the pump power increases, the enhancement of SBS gain decreases slightly but shows obvious gain enhancement at all pump power cases.

Except for this result, we also repeat the same experiment with another two materials (Black Phosphorus and Graphene) based on SMF. Black Phosphorus also contributes 0.4 dB SBS gain enhancement, while graphene does not (as discussed in previous study [5], the SBS frequency shift of graphene is about 40 GHz, hence far away from the SMF). Therefore, we can draw a hypothesis that MoS_2, Black Phosphorus, SiO_2 may have the similar Brillouin frequency shift which is around 10.8 GHz, but MoS_2 has wider Brillouin spectral linewidth. The Raman peaks of these materials, which can show the natural characteristics of materials, are also similar, while graphenes Raman peak is far apart, supporting our hypothesis from another perspective.

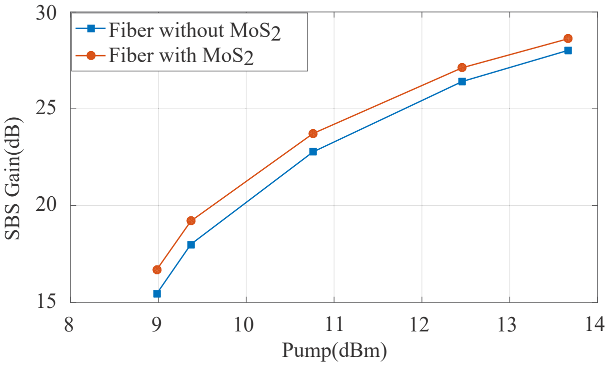

Fig. 6. SBS gain variation with pump power with and without MoS_2 on fibre end.

IV. CONCLUSIONS

Since generating microwave frequency and designing the microwave photon filter based on SBS are highly recommended now, various methods to enhance SBS effect are discovered constantly. Using special materials with such characteristics to reduce the physical size is desired. We have successfully transferred multilayer MoS_2 onto the fibre end with a new method and for the first time conducted an experiment to find whether MoS_2 can enhance SBS gain. The enhancement can be observed by 1.5 dB with about 48 layers MoS_2 only on the fibre end. Besides, we have also observed that this enhancement is existed within a range from 10.8GHz to 11GHz and affected slightly by the pump power. Finally, we have proposed an assumption to explain the enhancement according to the results.

V. ACKNOWLEDGEMENTS

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