Composite Material Hollow Core Optical Fiber Electro-Modulation

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Abstract: We demonstrate the integration of the Transition Metal Dichalcogenide (TMDC) materials WS_2 and MoS_2 into hollow core anti-resonant fibers. We show the potential to use such structures as all fiber electro-optical modulators.
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1. Introduction

Current hollow core fiber designs, such as the structure shown in Fig. 1(a), can support optical mode propagation through the air core of the waveguide via an anti-resonant mechanism [1]. Since the level of overlap of the guided light with the silica cladding region can be very low, the waveguide can exhibit several low loss anti-resonant transmission windows, even at mid-IR wavelengths where bulk silica has strong optical absorption [2]. The internal geometry of such a fiber also presents a large surface area that can be readily used as a template for the deposition of functional materials. Selective deposition both radially and longitudinally allows for the optimization of light-matter interaction. For example, if material deposited on the core walls of the waveguide generates too much loss, the deposition parameters can be modified such that the synthesis only occurs in the cladding area of the fiber. In previous work, we have used borosilicate based, tubular anti-resonant fibers (ARFs) as deposition templates for thin silicon layers [3], to create a novel composite material structure (CM-ARF) in which the waveguide properties are theoretically identical to that of a single material ARF with an equivalent refractive index and core wall thicknesses.

In the work presented here, the ARF fiber shown in Fig. 1(a) was functionalized using 2D transition metal dichalcogenides (TMDCs), specifically, MoS_2 and WS_2. These materials have been shown to exhibit excellent electro-refractive and absorption properties making them ideal for optical modulation [4]. Furthermore, the fact they exist in low dimensional form means that the addition of such a film will not substantially contribute to the scattering loss of an ARF. Very recently we have developed a facile deposition technique for these 2D layers inside hollow core fibers over extended length scales of order 30cm. These fibers remain relatively pristine post- 2D layer processing, thus resulting in a new class of CM-ARF structure that exhibit electro-modulation depths of around 1.4 dB during our preliminary experimental electric field tests.

2. Experimental Methodology

To integrate 2D material into the fiber, we followed solution processing protocols from Liu *et al.* [5], who used a mixture of amino/amine based solvents with a single source precursor. This solution was then introduced into the optical fiber through capillary action followed by a 500^{o}C anneal. Raman spectroscopy and White Light Source (WLS) measurements were taken on the fiber to characterize the deposition. A typical Raman trace of MoS_2 can be seen in Fig. 1(b), which is reproducible along the deposition length. This shows the two characteristic Raman peaks

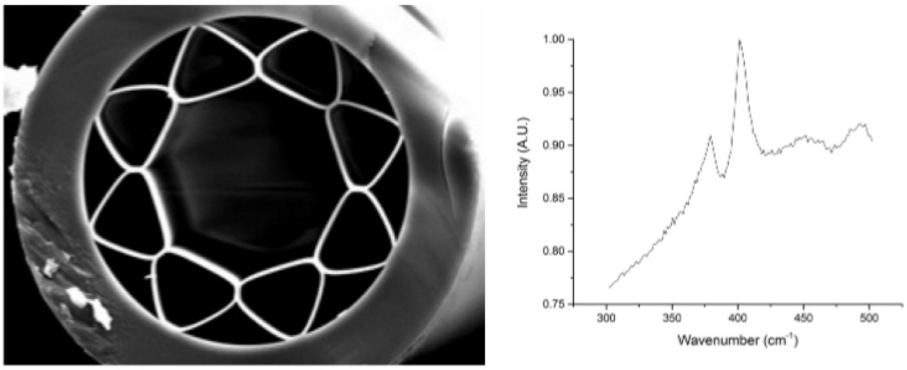

Fig. 1(a) shows an SEM image of the negative curvature fiber being used in the work. The triangular struts constitute the cladding. Fig. 1(b) shows a Raman spectrum for a MoS_2 integrated fiber, excited by a 532nm laser. The peak separation of 22cm^{-1} suggests a bi-layer film.

at 379.2cm^{-1} and 401.3cm^{-1}. This peak separation of 22.1cm^{-1} corresponds to the presence of a bi-layer film of MoS_2. For the WS_2 deposition, we also observed peaks at 353.0cm^{-1} and 415.7cm^{-1}, as expected from the literature when excited with a 532nm laser [6]. The fibers were functionalised with 2D materials in three permutations – only the core filled, only the cladding filled and both regions filled. The WLS transmission measurements can be seen in Fig. 2(a). These show how the transmission spectra changes between the three different configurations of layer deposition. To further investigate the properties of these CM-ARFs as electro-optical switches, the fibers were tested with an electric field applied across the deposited region. For this preliminary work, a simple metallic slab was placed underneath the fiber, to which a voltage of 0-1000V was applied. With this very simple setup, the electric field has to penetrate a significant dielectric barrier before interacting with the 2D material. This can be seen in Fig. 2(b) where the spectra changes modestly as a function of voltage, with 1.4 dB modulation seen at 740nm.

3. Experimental results and discussion

The three deposition configuration results can be seen in Fig. 2(a). The transmission spectrum shows the greatest change when the fiber of Fig. 1(a) has WS_2 deposited in the core region only. This is likely due to a higher modal interaction with the additional material. However, the spectrum in which WS_2 is deposited in both the core and cladding regions of the fiber shows lower scattering, suggesting that the anti-resonant properties may have been modified, allowing the mode to experience greater confinement. This appears to be confirmed by how the cladding only deposition spectrum shows minimal scattering loss. Therefore, for optimised 2D layer interaction with modest scattering loss, WS_2 deposited in both regions of the fiber was selected for further investigation in an electro-optic experiment.

The results of this can be seen in Fig. 2(b). The fiber shows a modulation in the 2nd transmission region (600-800nm) of around 1.4dB. The TMDC film interacts with an electric field in two ways [4]; a change in its refractive index and a change in its absorption coefficient. By changing the refractive index of the material, the guidance properties of the fiber will change, as per the condition given in reference [2]. By altering the absorption coefficient, the light overlapping the film is more likely to be absorbed and modulated.

Our future work will focus on improving the performance of the modulator, focusing particular attention on improving the very crude electric field setup that currently limits the overall electro-optical properties of this novel CM-ARF modulator device.

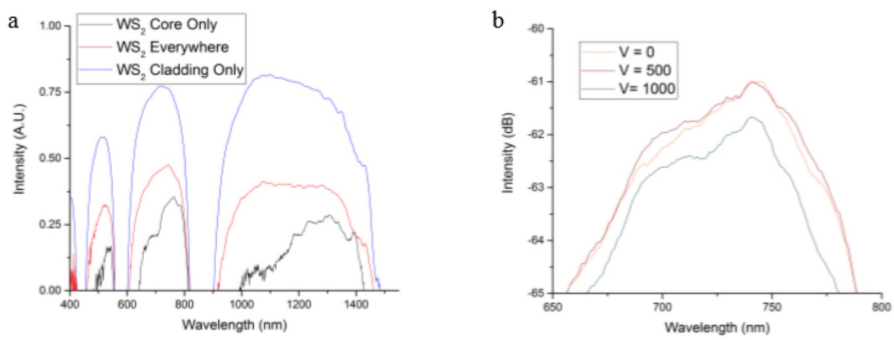

Fig. 2(a) shows how the spectra of the CM-ARF device changes with the different locations of WS_2 deposition. Fig. 2(b) demonstrates how the structure of Fig. 1(a) with WS_2 deposited in all regions of the fiber reacts with increasing voltage, exhibiting a maximum modulation depth of 1.4 dB.

4. References

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