

All-fiber loading sensor based on a hybrid 45° and 81° tilted fiber grating structure

Zhongyuan Sun, Zhijun Yan, Chengbo Mou, Xiangchuan Wang, Jianfeng Li and Lin Zhang

Abstract— We experimentally demonstrate an all-fiber loading sensor system based on a 45°- and an 81°-tilted fiber grating (TFG). We have fabricated two TFGs adjacent to each other in a single fiber to form a hybrid structure. When the transverse load applied to the 81°-TFG, the light coupling to the two orthogonally polarized modes will interchange the power according to the load applied to the fiber, which provides a solution to measure the load. For real applications, we further investigated the interrogation of this all fiber loading sensor system using a low-cost and compact-size single wavelength source and a power meter. The experimental results have clearly shown that a low-cost high-sensitivity loading sensor system can be developed based on the proposed TFG configuration.

Index Terms— Fiber optical sensors, Fiber optical gratings, Stress measurement.

I. INTRODUCTION

Due to their small size, lightness, long-term stability, immunity to electric-magnetic interference and most of all, the multiplexing capability, fiber gratings have been widely exploited as optical fiber sensors for measuring a range of physical parameters, including transverse loads. Transverse load sensors based on fiber Bragg gratings (FBGs) and long period gratings (LPGs) made in low-birefringence, hi-birefringence and multi-core fiber have been reported [1-4]. To function as loading sensors, the majority of these gratings exhibited a pronounced polarization mode split effect resulting from the birefringence induced by the transverse loading. Due to their high signal-to-noise ratio, narrow bandwidth and low threshold power, the fiber laser loading sensors incorporating the optical fiber gratings have become more attractive. A distributed-feedback (DFB) laser based loading sensor has been experimentally demonstrated by L.-Y. Shao *et al* [5], and Z. Sun *et al* [6] reported a single polarization ring cavity fiber laser for loading sensing.

Manuscript received XXX,xx 2015; revised XXX xx, 2015; accepted XXX xx, 2015. Date of publication XXX xx, 2015; date of current version December, 2013.

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Tilted fiber gratings (TFGs) were first reported by Meltz *et al* [7]. Zhou *et al* [8] experimentally demonstrated high polarization extinction ratio of in-fiber polarizers based on a 45°-TFG structure. Detailed experimental investigation and theoretical analysis on large angle TFGs have also been reported [9] by Zhou *et al*, revealing their forward-propagating cladding mode coupling function and strong polarization dependence. K. Zhou pointed out that the transmission spectra of large angle tilted fiber grating have a noticeable dual-peak feature and this feature is much more pronounced for an 81°-TFBG. Therefore, we prefer fabricated the 81°-TFBG for its sensing characters demonstration. The large angle TFGs have been proposed as fiber sensors for the detection of strain [10], twist [11], refractive index (RI) and liquid level [12, 13]. Due to its inherent polarization mode splitting effect caused by the asymmetric structure induced by the excessively tilted index fringes in the fiber core, a large angle TFG has been implemented as a novel in-fiber directional transverse loading sensor [14]. However, the interrogation of such a sensor requires an extra polarizer and polarization controller, imposing the disadvantages of complexity, bulk and cost.

In this paper, we report an all-fiber loading sensor system, which incorporates a 45°- and an 81°-TFG in a single piece of fiber. In this hybrid structure, the necessity of polarization controller is removed and the 45°-TFG is functioning as a linear polarizer which ensures the light launching to the 81°-TFG is at single polarization status, thus providing a simple solution to measure the transverse load using a low cost single wavelength source and a power meter.

II. THEORY AND FABRICATION OF 45° - AND 81° -TFGS

TFGs are capable of coupling the light from the forward-propagating core mode to backward-propagating, radiation and forward-propagating cladding modes when the tilt angle at <45°, =45° and >45°, respectively. The strongest coupling wavelength for a TFG can be given by the phase matching condition:

$$\lambda_{strongest} = (n_{co}^{eff} \pm n_{cl,m}^{i,eff}) \times \frac{\Lambda_G}{\cos \theta}, \quad i = \text{TE or TM} \quad (1)$$

Where n_{co}^{eff} and $n_{cl,m}^{i,eff}$ are the effective refractive index of core mode and m th TE/TM cladding mode, Λ_G is the grating period along the fiber and θ is the tilt angle of structure.

The hybrid TFG based loading sensor structure is shown in Fig. 1(a). The light pass through the 45°-TFG will filter out the

TE component and leave the TM component propagating in the 81° -TFG. Similar to a polarization maintaining (PM) fiber, we may define two orthogonal polarization axes to an 81° -TFG structure, as shown in Fig.1 (a). In this figure, the direction in the plane may be regarded as the slow axis, and the direction perpendicular to the grating fringe plane the fast axis. The effective refractive index along the fast axis and slow axis can then be expressed as n_f and n_s , and we have $n_f < n_s$. Fig. 1 (b) and (c) show the images of a UV-inscribed 45° -TFG and an 81° -TFG in the fiber core that were inspected by a microscope system (Zeiss Axioskop 2 mot plus) under a $100\times$ oil immersion objective lens.

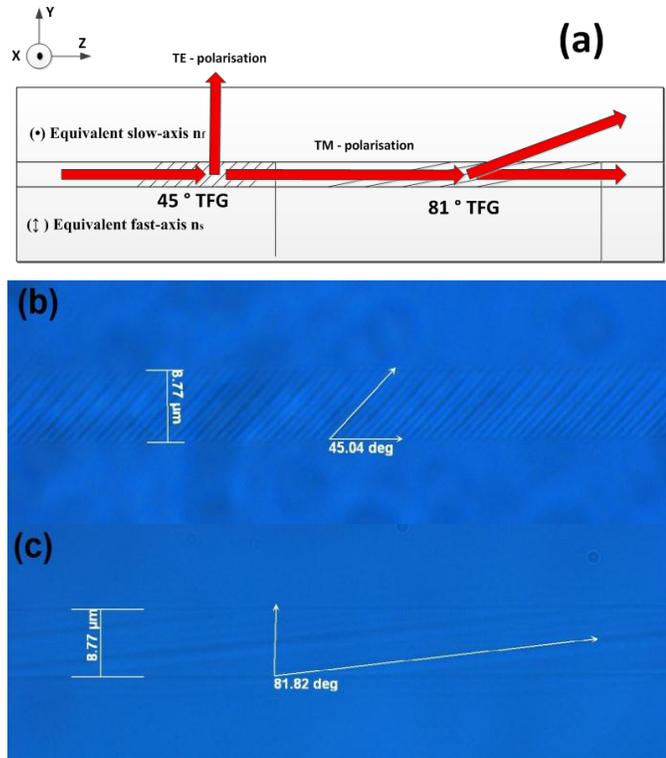


Fig. 1 (a) Schematic of a hybrid structure comprising a 45° and an 81° tilted fiber grating; the microscopy images of 45° -TFG (b) and 81° -TFG (c) in fiber core.

In the work reported in this paper, the 45° - and 81° -TFG were UV inscribed in Corning SMF-28 fiber using the scanning mask technique. The SMF-28 fiber was hydrogen loaded at 150 bars at 80°C for 48 hours prior to the UV exposure to enhance the photosensitivity. The 45° -TFG was firstly UV-written in the middle section of a 50 cm long fiber using a phase-mask with a uniform period of 1800nm and 33.7° tilted pattern on the glass substrate, which was designed for obtaining the polarization response centred around 1550 nm region. The tilted pitch pattern in the phase-mask is 25 mm long, thus, the effective length of 45° -TFG is around ~ 25 mm. In Fig.1 (b), we can clearly see that the tilted angle of the grating is measured at 45.04° , and the area of grating covers the entire fiber core (the diameter of the core of a standard single-mode fiber is $8.77\mu\text{m}$). For the 45° -TFG to function as an in-fiber polarizer in the load sensor system, its Polarization Dependent Loss (PDL) was evaluated. Fig. 2 shows the PDL spectral response of the

45° -TFG which was measured by using a commercial optical analysis system (LUNA optical vector analyzer). It can be clearly seen in Fig.2 that the other half of the Gaussian shape should be within the range of 1530 nm to 1610 nm. One may notice that there are spectral ripple of the grating overall PDL profile when the device is exposed to air (black solid line). This is because the cross coupling between the forward propagating core mode and radiation modes resulting from the refractive index mismatch between the air and cladding. In order to eliminate this resonance effect, the grating area of this 45° -TFG was immersed into index matching gel to achieve the infinite cladding boundary condition. As clearly shown in Fig.2, all ripples have been eliminated and the overall PDL profile is a smooth curve as shown by the red plot. Quantitatively speaking, we can see the PDL is about 15 dB around wavelength 1550 nm and dropped to 12 dB at 1600 nm. The 12 mm-long 81° -TFG was then UV inscribed adjacent to the 45° -TFG in the same SMF-28 fiber using a commercial amplitude-mask with a period of $6.6\mu\text{m}$ and the mask was rotated at 76.5° to induce 81° tilted structure in the fiber core. Fig. 1 (c) shows the image of the tilted fringes of an 81° -TFG under a microscope. The tilted angle of the fringes is measured at 81.82° , which is in good agreement with the design parameter. The typical measured transmission spectrum of an 81° -TFG shows a series of dual-peak loss bands in the wavelength range from 1250 nm to 1650 nm, corresponding to the two sets of coupled cladding modes with orthogonal polarization (inset of Fig. 3). The transmission spectra of one of the paired peaks for two (labelled as P1 and P2) orthogonally polarized states is shown in Fig 3. From the figure we can see that when the grating is probed with randomly polarized light, the two peaks show similar strength, e.g. 3-dB transmission loss; while when it launched with orthogonally polarized lights (P1 or P2), one of the dual peaks grows to its full strength (~ 11 dB) whereas the other almost disappears.

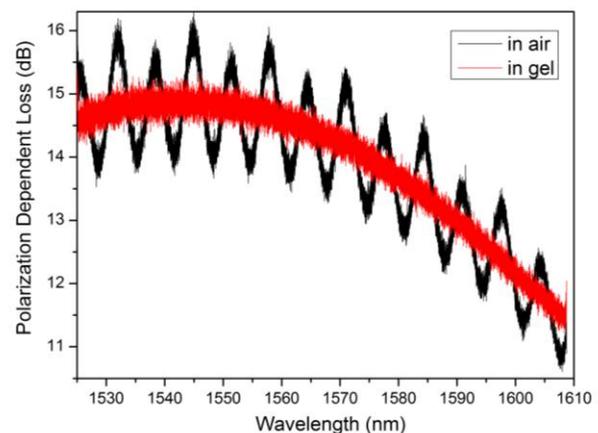


Fig. 2 The PDL spectral response of the 45° -TFG measured in air (black curve) and in index matching gel (red curve).

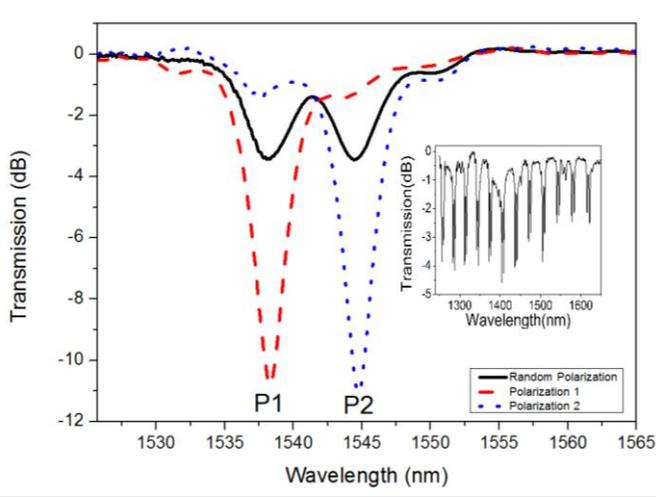


Fig. 3 The transmission spectra of 81°-TFG with one pair of the dual peaks for two orthogonally polarized states and randomly polarized state. The inset is transmission spectrum from 1250 nm to 1650 nm.

In this case, the 81°-TFG behaves more like a polarization maintaining (PM) fiber, preventing the change of the light coupling to the two polarized modes. When the transverse loading is applied to the y-axis of 81°-TFG fiber as shown in Fig 4, the refractive index changes in the cross section due to the photo-elastic effect can be expressed by [15]

$$\Delta n = n_x - n_y = (n_{x0} - n_{y0}) + (C_1 - C_2)(\delta_x - \delta_y) \quad (2)$$

where n_{x0} and n_{y0} are the effective refractive indices of the fiber; C_1 and C_2 are the stress-optical coefficients, δ_x and δ_y are the stresses in x- and y-direction. For silica, the C_1 & C_2 are constant and always positive. Based on reference [16], the horizontal normal stress δ_x is always positive (tensile) and the vertical normal stress δ_y is negative (compressive), which means $(\delta_x - \delta_y)$ is positive. Thus, the value of birefringence Δn is depending on the effective refractive indices of the fiber δ_x and δ_y . When the transverse load is applied to the fast axis of the 81°-TFG, we have $n_{x0} = n_s$ and $n_{y0} = n_f$ and the first term in equation (2) will be positive, resulting in increase in birefringence Δn . When the transverse load is applied to the slow axis of the 81°-TFG, the birefringence Δn will be decreased. The force induced by the load changes the birefringence Δn which in turn changes the polarization states of the polarized light thereby showing the variation in the peaks in the spectrum.

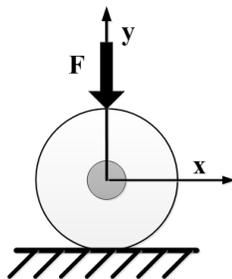


Fig 4 The cross section of a fiber in an assigned x-y coordinate system with transverse load applied along the y-axis. The x-y coordinate system is also depicted in Fig1 (a) for the 81°-TFG structure.

III. EXPERIMENTAL SET UP FOR LOAD SENSING AND RESULTS

Prior to load sensing, we have measured the temperature sensitivity of the 81°-TFG in order to evaluate cross-talk. Fig. 5 shows the set up for temperature response evaluation using a Peltier, which is a thermal transmission tool with electronic control. The temperature was increased from 0 °C to 80 °C with 10 °C increment. It has been reported in Zhou's paper [9] that the period A of TFG is the dominant factor on the thermal-induced wavelength shift. According to the mask period that we used in the work reported in this paper, the period of 81°-TFG is 8.9 μm , which is one order of magnitude short comparing with conventional LPGs (usually in several hundred μm s). The thermal-induced wavelength shift of the 81°-TFG is plotted in Fig. 6. As shown in the figure, the thermal sensitivity is only around 7.6 pm/°C, which is one order of magnitude lower than that of LPG, even less than the FBG. In other words, the thermal effect to our loading sensor is smaller than FBG and LPG which is desirable as practical loading sensors.

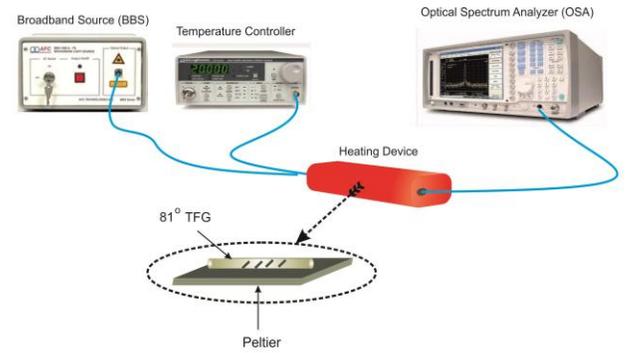


Fig. 5 The experiment setup for investigating temperature sensitivity of hybrid TFG based load sensor.

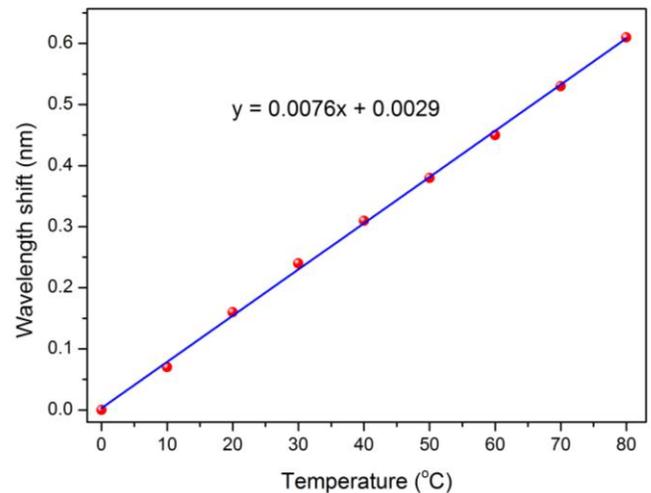


Fig 6 The wavelength shift versus temperature showing a low thermal cross sensitivity (7.6pm/°C).

The experimental setup of the load sensing is illustrated in Fig 7. Initially, the light from a broadband source (BBS) was launched into the 45°-TFG to be polarized before entering the 81°-TFG and the output was monitored from the other fiber end

by an optical spectrum analyzer (OSA). The 81°-TFG was laid between two flat-surface aluminum plates with a dummy fiber for balance. The active loading length between the two plates is 32 mm. In order to eliminate measurement errors from axial-strain and bending effects, the 81°-TFG was fixed on the plate with a small axial tension to maintain it straight.

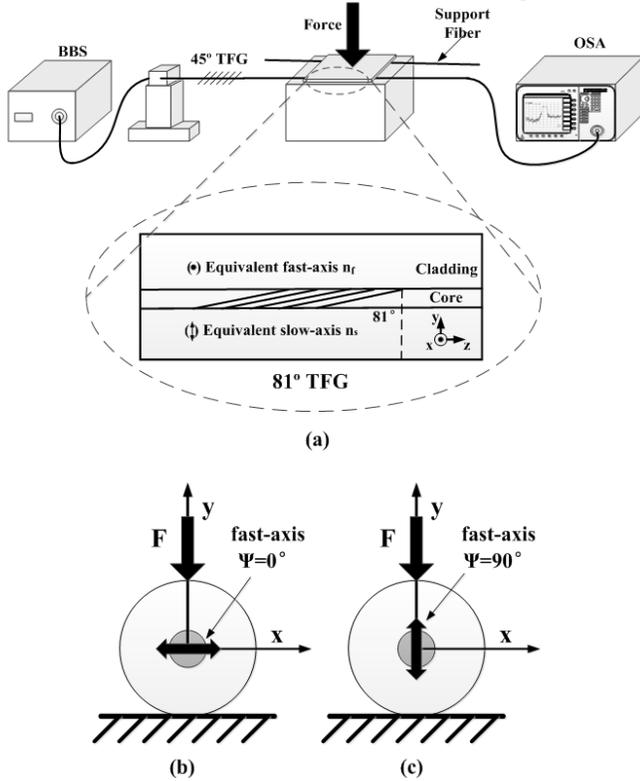
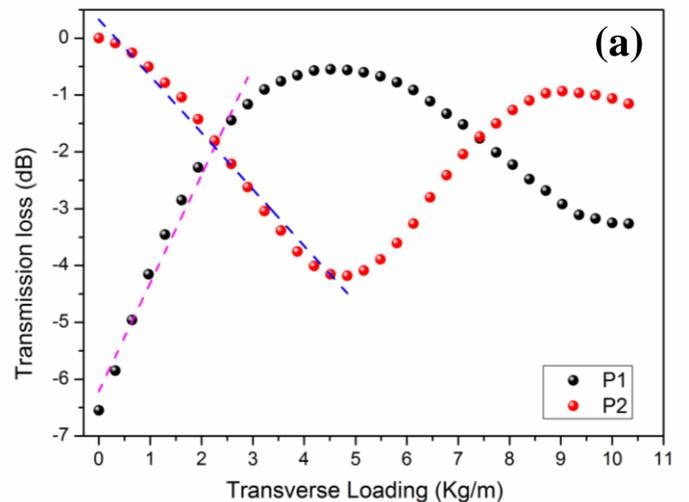
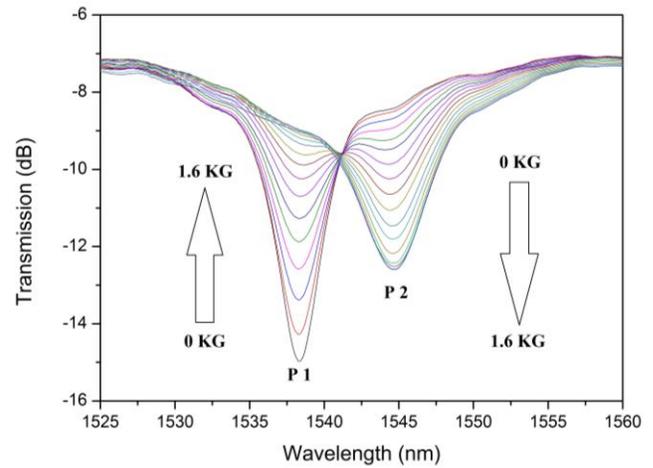


Fig. 7 (a) The schematic diagram of the all-fiber transverse loading sensor based on a 45°-TFG and an 81°-TFG. The 81°-TFG in a x-y coordinate system showing transverse load applied to its (b) fast-axis and (c) slow-axis.

We applied the transverse load first to the equivalent fast-axis of 81°-TFG from 0 to 1.6 kg in a step of 0.1 kg by putting the weights on the top of the aluminum plate, as shown $\psi = 0^\circ$ in Fig 7(b). The transmission spectrum for each applied load is plotted in Fig 8. As clearly seen, when the load was applied to the 81°-TFG, the P1 mode peak was gradually decreasing but P2 peak oppositely increasing, due to the load induced polarization state change. Due to applying the loading force to the sensing structure by using metal weights, the experiment results have been measured in unit “kg/m”. Fig 9 (a) plots the transmission loss against applied load for both peaks. We can see from Fig 9 (a) that for the loading range from 0 to 2.9 kg m⁻¹ for peak P1 and 0 to 4.5 kg m⁻¹ for P2, the transmission loss changes are almost linear, in which we estimate that the loading sensitivities are approximately 1.902 dB/ (kg· m⁻¹) and 1.023 dB/ (kg· m⁻¹) respectively. Although we see the load-induced transmission loss goes through a cycle (maximum – minimum – maximum), however, the intensity of peak P1 is not able to return to the initial point level with the cycles. The reason for this phenomenon is that the fiber deformation by transverse force induces the extra loss to the fiber waveguide. This loss will affect the loading sensitivity and limit the measurement range.

We then repeated the loading experiment by applying the transverse load to the grating slow-axis, as shown $\psi = 90^\circ$ in Fig 7(c). By increasing the force applied to the 81°-TFG, the P1 mode peak was decreasing, whereas the P2 peak was oppositely increasing, exhibiting a similar phenomenology to the case with the load applied to the grating fast-axis. However, it can be seen clearly from Fig. 9(b), the intensity of both peaks of 81°-TFG will eventually decreased by further increasing the loading force. This may be explained by the fact that the birefringence Δn will be reduced with increasing load when the loading force applied to the slow-axis of the 81°-TFG [10]. Thus, the low birefringence cannot maintain the light in two polarization states. As shown in Fig 9(b), the transmission loss changes by loading to the slow-axis are almost linear for the loading range from 0 to 4.2 kg m⁻¹ for peak P1 and 0 to 5.2 kg m⁻¹ for P2, in which we estimate that the loading sensitivities are approximately 1.365 dB/ (kg· m⁻¹) and 0.491 dB/ (kg· m⁻¹) respectively. We can see for loading to the slow-axis, the initial linear response range is larger than for loading to the fast-axis, but the loading response degrading much significantly with further increased loading.



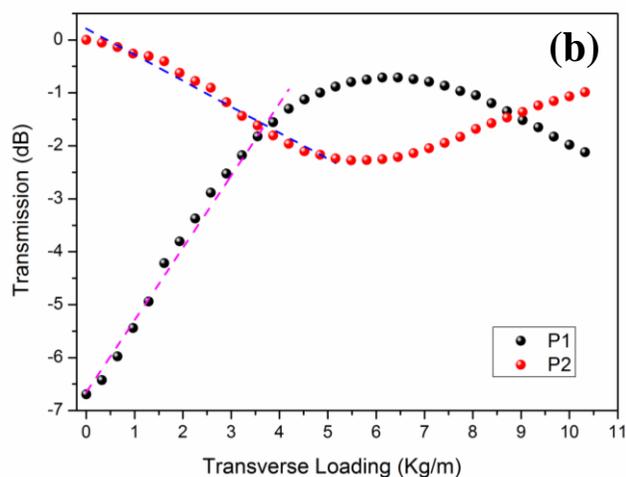


Fig 9 (a) Transmission losses of the two orthogonal polarization modes plotted with increasing load to fast ($\psi = 0^\circ$) axis. (b) to slow ($\psi = 90^\circ$) axis.

IV. LOADING MEASUREMENT USING A SINGLE WAVELENGTH LASER AND A POWER METER

From the above experimental results, we can see the load only induces a power coupling exchange between the dual peaks with orthogonal polarization states. Thus, the hybrid TFG based loading system may be interrogated using a low cost power measurement, which is much more desirable for real applications. To this end, we have replaced the BBS and OSA in Fig7 (a) with a tunable laser (in a real application, this can be a cheap single wavelength laser diode) and a power meter respectively, the schematic diagram is shown in Fig 10.

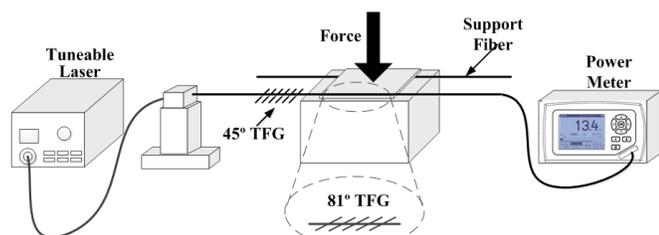


Fig 10 The schematic diagram of the transverse loading experiment system using a single wavelength source and a power meter.

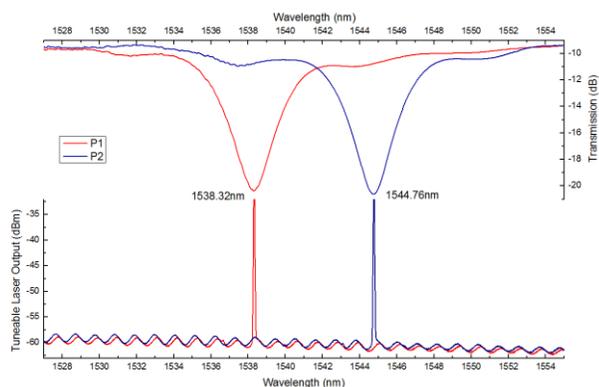


Fig 11 The upper plot is the transmission spectra of paired polarization peaks of 81° -TFG; the wavelength of the P1 loss peak is at 1538.32 nm and that of the P2 peak is at 1544.76 nm. The lower plot is the output spectra of the tunable laser set at the wavelengths of 1538.32 nm and 1544.76 nm, separately.

The spectra of the paired polarization peaks (1538.32 nm and 1544.76 nm) of 81° -TFG under loading are shown in Fig 11. In the experiment, we first tuned the laser to the P1 peak at 1538.32 nm and applied the load from 0 to 3.2 kg with an incremental of 0.1 kg to the 81° -TFG fast-axis and recorded the power reading accordingly, and then repeated this measurement by tuning the laser to match P2 at 1544.76nm. Fig 12 plots the measured power values against the applied load for the two peaks. Clearly, the load can be measured up to the range of 10kg/m. Although the entire plots are not linear, there is an almost linear loading response range from 0 to 3.5 $\text{kg}\cdot\text{m}^{-1}$ for peak P1 and from 0 to 4.0 $\text{kg}\cdot\text{m}^{-1}$ for peak P2, in which we estimate that the loading sensitivities are approximately $30.142 \mu\text{W}/(\text{kg}\cdot\text{m}^{-1})$ and $16.319 \mu\text{W}/(\text{kg}\cdot\text{m}^{-1})$ respectively. As the load is measured in electronic signal form, this may provide a mechanism that potentially the signal may be transmitted wirelessly for remote control and monitoring.

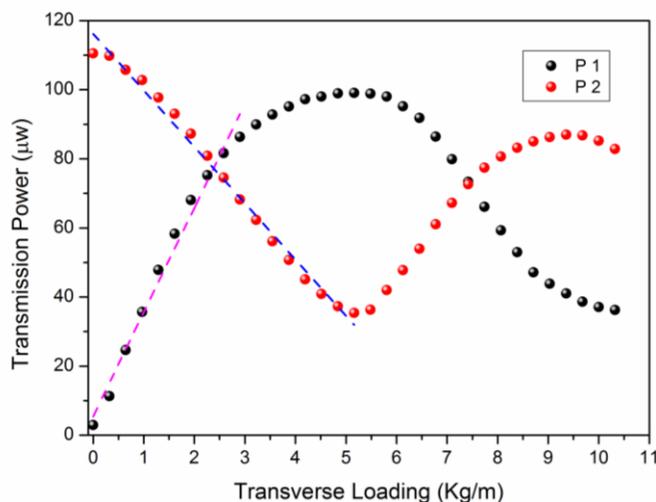


Fig 12 Transmission powers variation for the two orthogonal polarization peaks measured using the tunable laser and power meter.

V. CONCLUSION

In conclusion, we have demonstrated an all-fiber loading sensor based on a hybrid 45° - and 81° -TFG structure. Such a sensor system removes the use of the commercial polarizer and polarization controller, making the sensor system more simple and compact. More importantly, such a TFG based loading sensor can be demodulated using low-cost intensity measurement by employing a single wavelength laser and photo detector, which is more suitable for real applications.

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