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Fabrication of Long Period Fiber Bragg Grating Based on Photonic Crystal Fiber Using CO_2 Laser

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Abstract

Photonic crystal fibers (PCFs) are generally divided into two categories: solid-core photonic crystal fibers and hollow-core photonic crystal fibers. In this paper, a long-period fiber Bragg grating (LPFBG) was experimentally fabricated in a hollow-core photonic crystal fiber (HC-PCF) using a CO_2 laser and based on the point-by-point technique. Proper LPFBGs were inscribed using laser powers of 0.9 W and 1.4 W, with grating parameters (grating period, length of each pitch, and depth of each pitch) equal to (136 μm, 48.042 μm, 16 μm) and (142 μm, 74.027 μm, 22.09 μm), respectively, for two samples. The Bragg wavelengths and full-width at half-maximum (FWHM) were (1529.274 nm, 1.34 nm) and (1529.629 nm, 5.11 nm), respectively, for the two samples fabricated using CO_2 laser powers of 0.9 W and 1.4 W. From these results, it was recognized that the optimal LPFBG-HC-PCF was the one fabricated using 0.9 W laser power. The unique structure of hollow-core photonic crystal fibers, which enables light propagation within the air core and provides a large internal surface area, has attracted significant research interest for various sensing و communication applications, Environmental and Biological Monitoring, and medical applications.

Keywords: Long Period Fiber Bragg Grating, Point by Point Technique, Photonic Crystal Fibers, CO_2 Laser.

تصنيع الياف براك المحززة طويل الفترة بناءا على الالياف البلورية الفوتونية باستخدام ليزر ثاني أكسيد الكاربون

نداء لفتة محجوب، انوار عبد الستار الدركزلي

الخلاصة:

تُقسم الألياف البلورية (PCFs) الفوتونية بشكل عام إلى فئتين: الألياف البلورية ذات النواة الصلبة، والألياف البلورية ذات النواة المجوفة. في هذا البحث، تم تصنيع براك طويل المدى (LPFBG) تجريبيًا داخل ألياف بلورية فوتونية ذات نواة مجوفة (HC-PCF) باستخدام ليزر ثاني أكسيد الكربون (CO_2) وباعتماد تقنية النقطة تلو الأخرى (Point-by-Point). تم حفر براك LPFBG باستخدام قدرتين لليزر تبلغان(٠,٩ واط و١,٤ واط)، مع معلمات البراك تشمل (فترة البراك، وطول كل حز، وعمق كل حز) تساوي (١٣٦ مايكرومتر، ٤٨,٠٤٢ مايكرومتر، ١٦ مايكرومتر) و(١٤٢ مايكرومتر، ٧٤,٠٢٧ مايكرومتر، ٢٢,٠٩ مايكرومتر) على التوالي لعينتين مختلفتين.. كانت أطوال موجة براج والعرض عند نصف القيمة العظمى (FWHM) تساوي (١٥٢٩,٢٧٤ نانومتر، ١,٣٤ نانومتر) و(١٥٢٩,٦٢٩ نانومتر، ٥,١١ نانومتر) على التوالي للعينتين المصنوعتين باستخدام قدرات ليزر CO_2 (٠,٩واط و١,٤ واط) . من خلال هذه النتائج، تم التوصل إلى أن أفضل LPFBG-HC-PCF هو ذلك الذي تم تصنيعه باستخدام قدرة ليزر تبلغ(٠,٩ واط.) . إن التركيب الفريد للألياف البلورية الفوتونية ذات النواة المجوفة، التي تسمح بانتقال الضوء داخل النواة الهوائية وتوفر مساحة سطحية داخلية كبيرة، جذبت اهتمامًا بحثيًا كبيرًا لتطبيقات متعددة تشمل التحسس، والاتصالات، والرصد البيئي والبيولوجي، والتطبيقات الطبية.

1. Introduction

Fiber Bragg Grating (FBG) technology was first introduced by Ken Hill in 1978 at the Communications Research Centre Canada [1]. A fiber Bragg grating is simply a one-dimensional periodic modification of the refractive index of an optical fiber's core. This modulation is often achieved by taking use of the fiber material's photosensitive properties. FBGs are popular because of their easy production method and ability to create a high-reflectivity signal, making them ideal for optical sensing applications. Fig. 1 depicts the usual reflection and transmission spectra of a fiber Bragg grating, which demonstrate the phase-matching resonance process. FBGs' selective wavelength reflection feature makes them perfect for applications in optical filtering and wavelength-specific sensing. Early research largely focused on their usage in telecommunications for wavelength division multiplexing (WDM) systems due to its ability to reflect select wavelengths while transmitting others [2]. Over the years, the distinctive qualities of FBGs—such as wavelength selectivity, immunity to electromagnetic interference, and multiplexing capability—have eased their translation into numerous sensing applications. In parallel, the development of Long-Period Fiber Gratings (LPFGs) has added a new dimension to fiber optic sensing. Unlike FBGs, which reflect narrowband light, LPFGs couple light from the core mode to cladding modes, resulting in attenuation bands in the transmission spectrum [3].

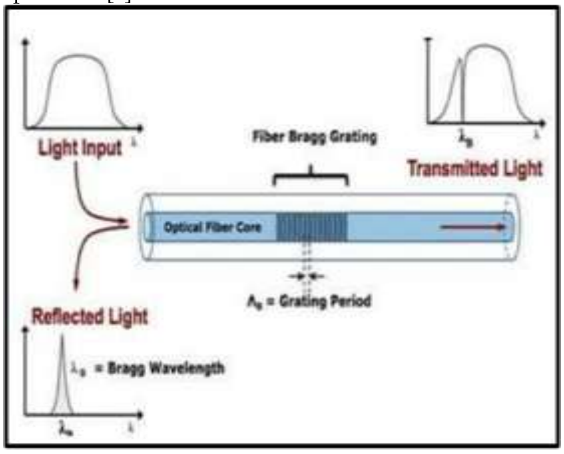

Figure (1): Schematic structure of a Fiber Bragg Grating (FBG) illustrating the reflected and transmitted light spectra, including the corresponding output spectral response [4]

Fiber bragg gratings are classified into two types: fiber Bragg gratings (FBGs) with periodicities like optical wavelength called short period fiber bragg grating and fiber gratings (LPFGs) with periodicities of various hundred wavelength call long period fiber bragg grating (LPFBG)[5] .The center wavelength of short period fiber bragg grating is given by equ.[6]

$$\lambda_B = 2 \; n_{eff} \, \Lambda \qquad \ldots\ldots (1).$$

Where λ_B is the center wavelength of the reflected light (Bragg wavelength), n_{eff} is the effective refractive index qualified via optical of mode narrowed to core at λ_B, and Λ is period of bragg grating .The bragg wavelength λ_B for an LPFG with period of grating Λ is found by phase matching condition as shown in equ.[7] .

$$\lambda_B = (n_{core,eff} - n_{cladding,eff}) \, \Lambda \quad \ldots\ldots (2)$$

Where $n_{core,eff}$ and $n_{cladding,eff}$ defined as effective refractive index of the central core, and cladding mode respectively.

Long-period fiber Bragg gratings (LPFBGs) have recently received a lot of attention for their adaptability in a variety of applications, such as band-rejection filters, gain equalization, and sensor technologies [8]. LPFBGs are made in a similar way to short-period gratings, but with an amplitude mask instead of a phase mask. In this work, the point-by-point inscription approach described by Malo et al. [9] is used. This approach focusses a laser beam on a tiny part of the fiber, causing localized changes in the refractive index. Both UV pulsed lasers and femtosecond lasers may be utilized to create complicated grating structures. However, there are significant limits to the point-by-point technique. These include the time-consuming nature of the procedure, the difficulties in generating gratings longer than 1 cm, and the exact alignment required by the computer numerical control (CNC) translation step to correctly concentrate the laser beam on the fiber segment [10]. Despite these challenges, the point-by-point method offers significant flexibility in tuning key parameters of the FBG, such as grating length and period. Although this method may result in lower contrast compared to the phase mask approach, it allows for precise customization, which is beneficial for creating long-period gratings [11].

The primary aim of this study is to fabricate LPFBGs and evaluate their performance as sensors for various parameters, including blood glucose levels, strain, temperature, and refractive index.

2.Fabrication FBG techniques

Long period gratings (LPFGs) can be manufacture utilize one method of internal or exterior inscription methods. External inscription methods, such as amplitude splitting, wavefront splitting, interferometry, masking of phase, and point by point method, are broadly utilized to get several goals, but internal inscription is useless method because it not active. These Different fabrication methods, involving UV laser exposure, CO_2 laser irradiation [12], electric discharge, femtosecond laser exposure [13], mechanical microband, and engraved corrugation, which utilized to inscribe LPFGs in various optical fibers.

The CO_2 laser irradiation technique is best and practical compared with ultraviolet (UV) laser technique for several reasons such as flexible, low cost, no need for photosensitivity and, no need for pretreated process when inscribe grating in fiber [14,15]. so, this technique used to fabricate LPFGs in most types of optical fiber such as single mode fiber (SMF), multimode fiber (MMF), no-core fiber (NCF), and photonic crystal fibers (PCFs). Since Davis et al. indicated the first CO_2 -laser-induced LPFG in a standard silica fiber in 1998[16,17]. Different CO_2 laser beam methods have been proved and enhanced for writing excellence LPFGs in various categories of optical fibers, which include standard silica fibers, PCFs, and PBFs, while achieving specific grating properties. The CO_2 laser irradiation produces unexpected physical changing in fiber structure during fabrication LPFBG. This physical changing is prevented to reduce the insertion loss of the inscribed

LPFGs due to initial grating inscriptions by the CO_2 laser beam.[18].

3. Inscribed LPFGs in hollow core photonic crystal fiber (HC-PCF)

Several gratings have been generated inside various kinds of PCF by the utilize different techniques of inscription. these grating were inscribed in index guiding PCF rather than bandgap guiding fiber or called hollow core fiber. In past, HC fiber-based grating was inscribed in new type of bandgap guiding fiber like fluid filled PBF [19] and totally solid- PBF. But, PBF based gratings not related in hollow core PBFs until realization in inscribing excellence LPFBG in the hollow core PBF [20]. PBF has different characteristics for instance high dispersion, low nonlinearity, decreased sensitivity of environment, and abnormal mode coupling. Therefore, exhibited the experimental possibility of inscribing the grating in HC-PCF. To produce high quality LPFBG in HC-PCF requires achieving, exceptional stability in power for CO_2 laser, and the accurate repeatability for scanning. Compared with inscription parameters for fabricating the grating into solid core PCF the lesser average power for laser around 0.2 W, and less whole time of laser beam was utilized for inscribing the HC-PCF [21,22].

4.Experimental setup and preparations

The experimental setup used for fabricating LPFBGs in hollow-core photonic crystal fibers (HC-PCFs) using a CO_2 laser and based on the point-by-point technique is schematically illustrated in Fig. (2).

This setup consists of the following main components: HC-PCF (Thorlabs: 1550-02) – the target fiber in which the long-period fiber Bragg grating (LPFBG) is inscribed, Single Mode Fiber (SMF, Corning SMF-28) a standard silica fiber with a core/cladding diameter of 9/125 µm, which is used for splicing to the HC-PCF to enable proper light coupling and characterization, CNC-Controlled CO_2 Laser System – this is the core component of the setup and includes(A CO_2 laser source with a maximum output power of approximately 100W, Operating wavelength of λco_2= 10.6 µm, a transition stage with a movement speed of 2.9 mm/s, a precision-controlled CNC stage for accurate fiber positioning, an objective lens for focusing the laser beam onto the fiber surface, a software-controlled system for synchronization and automation, a water chiller to maintain stable operating temperature of the laser source, all of these components work in coordination as a complete CO_2 laser workstation .

The fabrication LPFBG based HC-PCF steps as follow :firstly , tacking about 5cm length of HC-PCF cutting from two ends , cleaning and putting under CO_2 laser beam, secondly : set properties of CO_2 laser such as (power ,time ,number of grating , number of groves, length of grating, and period of grating Λ) and began with operate CO_2 , (set CO_2 concentrated on the middle of PCF that is mounted on a stage of aluminum inside CO_2 to obtain perpendicular beam during inscription process. The CO_2 laser beam focus on short piece of HC-PCF about (5 mm), condition length of grating (< 1cm), because using point- by-point method for fabrication LPFBG. Third and lastly step carrying the inscribed HC-LPFBG fiber for testing under optical microscope (ALTAY, Biolab Line) to ensure from formation LPFBG in proper shape and measure grating parameters from images that taking under microscope**.** The use CO_2 beam tested continually the HCF with velocity of scanning about 3 mm/s, producing removal of silica from surface of fiber and the part or whole collapse of air holes in cladding through the CO_2 laser induced limited high temperature.

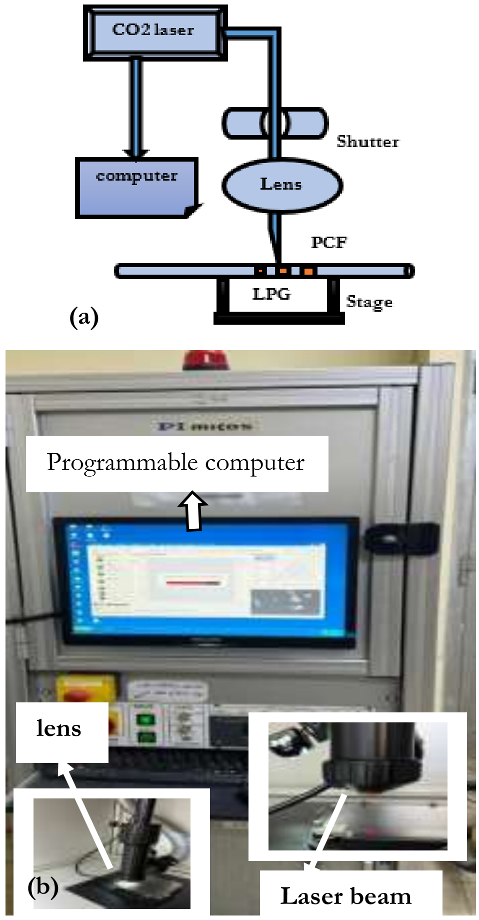

Figure (2): (a) Schematically diagram of fabrication process and (b) image of experimental CO_2 setup

4.1 Testing long period Fiber Bragg grating formation

A Long fiber- Bragg -Grating (LFBG)testing arrangement is represented schematically in Fig. (3). Set up of fabrication process involves: HC-PCF (1550-02), typical SMF needed it to splicing in two ends of PCF, computer, a white light source operational in the range 1520–1570 nm, and an optical spectrum analyzer (model: OSA-M-CFA.) resolution oof it equal 2~200 ppm applied to monitor and recorder transmission spectrum. Once the grating was inscribed, HC -PCF ends (with gratings that formation in the middle) were cleaved, cleaned and spliced to typical SMFs with (FC/FC) connectors, transmitting spectrum of the HC-LPFBG was measured via broadband source and OSA.

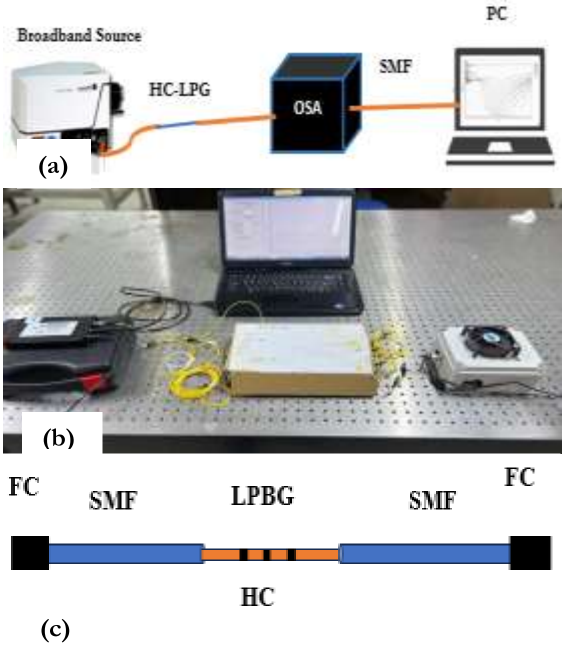

Figure (3): (a) Schematically diagram of HC-LPFBG examination process and (b) image of experimental setup, **(c)** Schematically splicing of LPFBG- HC -PCF that spliced with SMF with FC/FC connectors

After obtain microscopic image and measure LPFBG parameters, the inscribed fiber was spliced with SMF as shown somatically in (fig. 4.c) and testing it. the result from testing to ensure that LPFBG formation with good and proper transmission spectrum

5.Result and discussion

Five sample of long period Fiber gratings were fabricated, set different powers (0.6W,0.9W,1.4W,1.6W,1.9W) using CO_2 laser device deepened on the point-by-point (PbP) method to acquire the good grating for coming requests such as sensors and add-drop multiplexers. Some weakness detected through this fabrication process such as length of LPFBG should be short scale in (mm) to protect the fiber from melting, also calibration of CO_2 needed new work. In this paper initial power about (0.6 W) as minimum rate, until arrive (1.9 W) as maximum power rate, only two samples from these Five powers are success with (0.9W,1.4W) as proper grating. Investigate HC-LPFBG under the optical microscope after outing it from CO_2 laser box to check parameters of HC- LPFG, for two success sample. Putting this image in software program (Image J) to obtain (period of grating (Λ),width of each pitch(W), and depth of each pitch(D)) equal (136 um, 48.042 um, 16um), and (142um,74.027um, and 22.09um) respectively for two samples under microscope, and under fusion splicing device, and taking as shown in (Fig.4)

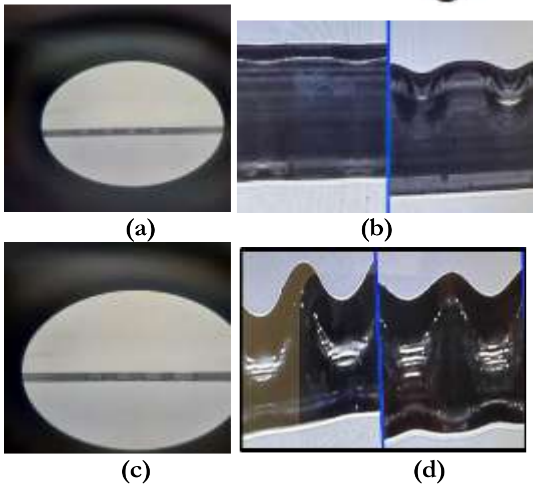

Figure (4) :(a, c) microscopic image of HC-LPFBG for two samples (0.9 W,1.4W) respectively, (b, d) fusion splicing images for (0.9W,1.4W) respectively.

While other samples with power less than 0.9W or above 1.6W are melting or not effected, or collapse holes or when increasing number of grooves, this lead to eliminate HC-LPFBG operation as shown in (Fig.5).

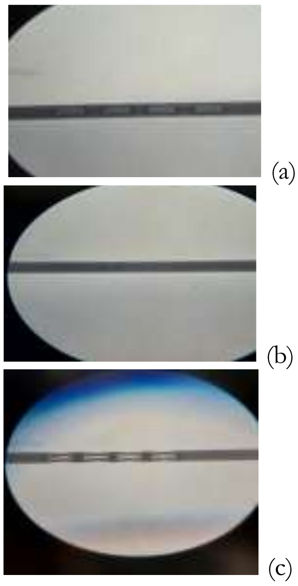

Figure (5): (a, b, c) microscopic image of HC-LPFBG for three samples (0.6W, 1.6W1.9W) respectively

The transmission spectrum for First sample, and the comparison, with and without HC-LPFBG shown in (Fig.6), the transmission spectrum of the HC-LPFBG exhibits several resonance dips between 1520-1570 nm, showing mode interaction between the core and cladding modes inside the photonic crystal structure. Bragg wavelength, and FWAHM of this grating equal 1529.274 nm, and 1.34 nm respectively. The somewhat narrow FWHM implies outstanding grating quality and effective mode coupling, making it ideal for high-resolution sensing and filtering applications. The smooth transmission curve indicates a uniform grating and high-quality inscription using the point-by-point technique.

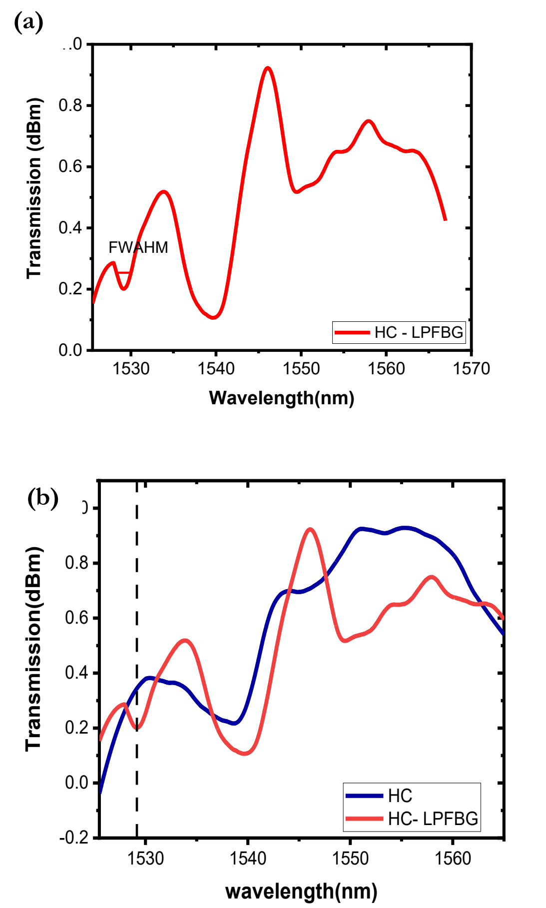

Figure (6): Transmission spectrum of HC-LPFBG-PCF for p= (0.9W), (a, b) with and without LPFBG

While the transmission spectrum for second sample with and without LPFBG, one of the key characteristics observables from the graph is brag wavelength, and the full width at half maximum (FWHM) of the primary resonance dip near 1529.629 nm, 5.11nm respectively, 1530 nm, which is marked in in (Fig.7). Comparing gratings fabricated at different laser powers (e.g., 0.9 W vs. 1.4 W), the shape and depth of the resonance can vary, with the 0.9 W grating generally providing sharper and more distinct spectral features.

Furthermore, we recommend improving parameters such as power, number of pitches, speed, and length of grating region on the fiber surface at the center to achieve an optimal and well-suited long period grating.

6.Conclusion:

This study successfully prepared a long-period fiber Bragg grating (LPFBG) in the hollow-core photonic crystal fiber (HC-PCF). The grating was inscribed using a CNC CO_2 laser with the point-by-point method. An experimental setup was employed to characterize the fabricated HC-LPFBG. Five HC-PCF samples were inscribed using a CO_2 laser at different power levels (0.6 W, 0.9 W, 1.4 W, 1.6 W, and 1.9 W) to produce LPFBGs. However, only two of these samples successfully formed proper LPFBGs, while the others showed no significant effect or experienced fiber melting due to excessive CO_2 laser power. Proved that point-by-point inscription HC-PCF is flexible, simple, and unexpensive. Also c... le that length of grating should be <1cm, and n... of pitches should be less than (5 pitch). Also concluded the CNC CO_2 laser device is an excellent choice for writing LPFGs, as it does not require photosensitivity or any pretreatment, making it a low-cost.

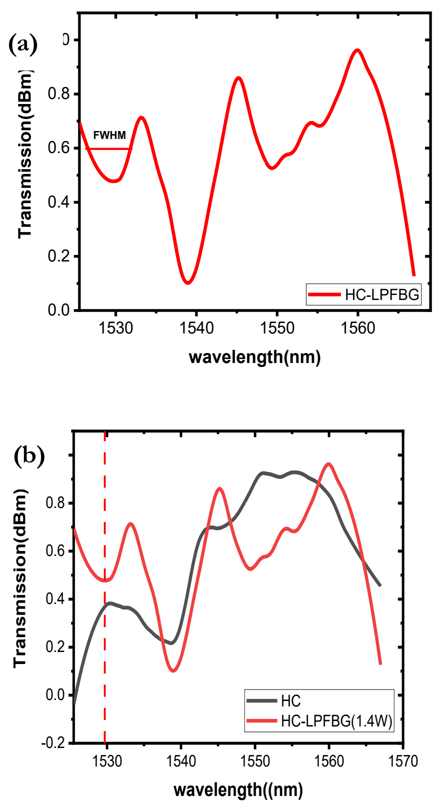

Figure (7): Transmission spectrum of HC-LPFBG-PCF for p=(1.4W), (a,b) with and without LPFBG

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