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Tapered and linearly chirped fiber Bragg gratings with co-directional and counter-directional resultant chirps

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ABSTRACT

A method of spectral width tailoring of tapered fiber Bragg gratings is theoretically analyzed and experimentally verified. This concept is based on inscription grating structures in which synthesis of chirps comes from both taper profile and a linearly chirped phase mask used for grating inscription. It is shown that under UV exposure and depending on the orientation of the optical fiber taper relative to the variable-pitch phase mask, tapered and linearly chirped fiber Bragg gratings (TCFBG) with resultant co-directional or counter-directional chirps are achieved. Thus, both effects, those of reduction and enhancement of the grating chirp, as well as their influence on the grating spectral response, are presented. In particular, using the above approach TCFBG with significantly narrowed spectral width are shown. Moreover, fused tapered chirped FBG with relatively large waist diameter are shown having broad spectrum, something that prior to now was not attainable using previously developed techniques.

1. Introduction

Among the variety of Bragg grating structures, extremely interesting are those written in tapered optical fibers. What distinguishes tapered fiber Bragg gratings (TFBG) is different strain and temperature responses. In the case of typical uniform fiber Bragg gratings (FBG), written in non-tapered optical fiber, both temperature and strain changes result in the same effect of a wavelength shift of the spectral response while maintaining the shape of the reflected spectrum [1]. On the other hand, when strain is applied to the tapered FBG, various local elongations appear due to the variable optical fiber diameter along the grating. Thus, under the influence of applied force, changes in width of the TFBG spectral response are observed. As for temperature variation, the effect is similar to that in uniform FBGs, where only the wavelength shift of the reflected spectrum appears [2]. Another important and unique advantage of TFBGs is the possibility of adjusting the slope of the group delay (GD) response, i.e. dispersion tuning. When the chirped FBG written in non-tapered optical fiber is strained, only the shift of the GD response occurs. However, in the case of tapered fiber Bragg grating, the slope of the group delay response can be also adjusted [3,4]. This in turn gives the possibility of designing tunable dispersion compensators and fiber optic components with variable group-delay for microwave photonics applications [5]. In addition, the main disadvantage of TFBGs is their relatively narrow spectral response, which affects the limitation of a common operation band of the tunable dispersion compensators [3]. Moreover, in sensing applications of TFBG, the requirement for wider spectral bandwidth is also desirable, because it allows for increasing the level of reflected optical power, and thus yields better dynamic range and measurement accuracy.

Typically, the spectral width of TFBG is only 3–4 nm for both fused and etched tapers with reasonable (i.e. tens of μm) waist diameters. It comes from relatively small changes of effective refractive index along the section of tapered optical fiber where the grating is written [3,6]. Moreover, the overall useful band of strain-induced adjustable dispersion compensators is significantly reduced to be no more than 1 nm, due to the simultaneous shift and spectral reduction of TFBG reflection spectrum [3]. A potential way to broaden the spectral response of TFBG is to achieve greater changes of effective refractive index in the tapered region of the optical fiber. In practice, it can be achieved by making optical fiber tapers with substantially reduced waist diameters on the order of less than 10 μm. This, in turn, makes the taper less resistant to tensile force, which significantly limits the range of applications, such as tunable compensators or strain sensors. Therefore, this method of broadening of TFBG spectrum can be used only in cases where the taper is not subjected to tensile force, for example in refractive index measurement [7]. Moreover, the reduction of optical fiber geometry in fused tapers results in the extension of the mode field diameter, which reduces the coupling coefficient and consequently causes a significant decrease of grating reflectance at the short-wavelength side [8].

Another way to modify the spectral width of grating spectrum

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is writing by means of uniform phase mask while the optical fiber taper is stretched [5,9]. After removing tension, the resultant spectral width increases due to the various local elongations in the tapered optical fiber during the grating exposure. Using this method, TFBG with 4.8 nm spectral width was obtained [6]. However, the presented technique does not allow for narrowing the spectral response of tapered fiber Bragg grating. Moreover, inducing broader reflected spectrum by means of elongation during grating exposure is substantially limited by the finite allowable amount of elongation. Furthermore, in the proposed technique it is difficult to fully control the resultant TFBG spectrum due to it changing once tension is removed. Therefore, it is not possible to precisely design the spectral shape of the TFBG, but rather only loosely predict it. However, in the case of complex taper profiles, even prediction is not an easy task.

In order to overcome aforementioned limitations, in this paper a new concept for spectral response engineering of tapered fiber Bragg gratings is presented. It is realized by obtaining novel fiber grating structures with unique resultant chirp induced by the specific irradiation method, where gratings are written in tapered optical fibers using a linearly chirped phase mask. Depending on the orientation of taper transition relative to the variable-pitch phase mask during UV exposure, FBGs called tapered chirped fiber Bragg gratings (TCFBGs), with reduced, as well as enhanced, chirp can be achieved. Using the proposed writing technique allows for obtaining TCFBGs with a wide range of precisely defined spectral widths. In particular, it is possible to achieve gratings with a broad reflected spectrum not previously attainable using prior known techniques, while maintaining relatively large taper waist diameter. Additionally, the presented method allows for fabrication of tapered chirped fiber Bragg grating with narrowed spectral width, as in the case of uniform FBG.

In this paper, theoretical analysis and an idea of inscription of new tapered chirped fiber Bragg structures is presented in detail. In particular, the possibility of obtaining gratings with chirp enhancement as well as chirp reduction is shown. Then, experimental results of TCFBG design and fabrication are presented. Measured spectra of gratings written in configurations of co-directional and counter-directional chirps, where effects of resultant chirp enhancement and reduction occur, are shown. Spectral responses of written gratings are compared with numerically calculated ones. Finally, a brief summary of the work is provided, where benefits of TCFBGs and their potential applications are presented.

2. Theoretical model

Let us consider the section of fused tapered optical fiber, where both cladding as well as core diameters are proportionally reduced and taper geometry ensures that the adiabatic criterion is met. In this case, the taper can be treated as a lossless passive optical fiber component, where the effective refractive index n_{eff} for fundamental mode LP_{01} varies with fiber core diameter d according to the implicit formula [10]:

$$\frac{2\pi}{\lambda}d(z)\cdot\left(n_{co}^2 - n_{eff}^2(z)\right)^{\frac{1}{2}} - \frac{\pi}{2} = 2\cos^{-1}\left(\frac{n_{co}^2 - n_{eff}^2(z)}{n_{co}^2 - n_{cl}^2}\right)^{\frac{1}{2}} \quad (1)$$

where λ is the wavelength of propagating mode, n_{co} is the refractive index of fiber core, n_{cl} denotes the refractive index of fiber cladding and z stands for propagation direction. This equation is used to numerically determining $n_{eff}(d)$, which is a basis for the further analysis of TCFBGs written in standard single-mode optical fibers with assumed n_{co}=1.4513 and n_{cl}=1.4440.

Let us also consider that the grating is written in both transitions of symmetrical optical fiber taper through the linearly chirped phase mask, and the grating as well as taper length equals. In this way, a Bragg grating with linearly variable period is obtained in accordance with the $\Lambda(z)$ characteristic shown in Fig. 1. In addition, n_{eff} along the taper profile also varies due to the variable optical fiber diameter. Thus, the relationship between local resonant (Bragg) wavelength of TCFBG and position along the taper can be written in the following form:

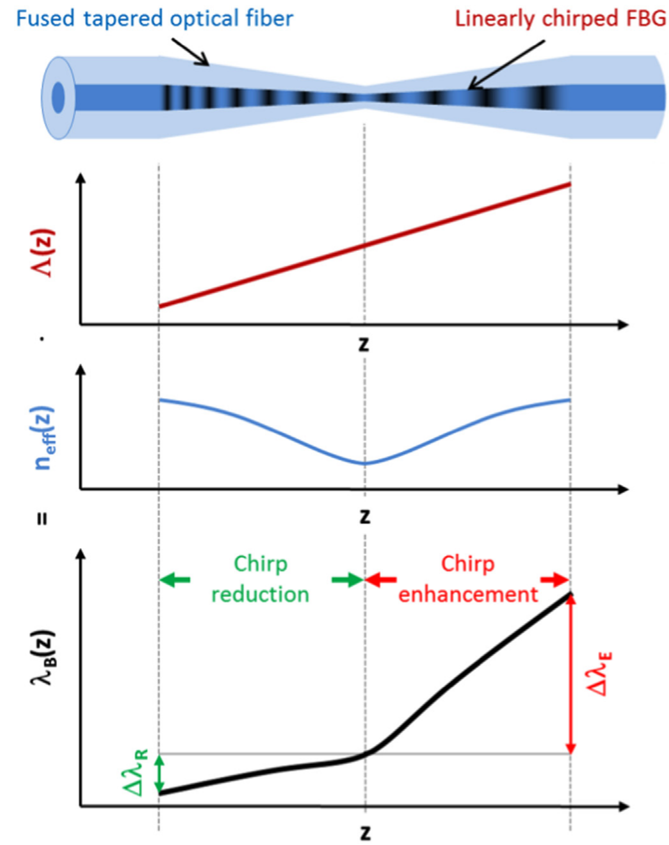

Fig. 1. An idea of TCFBG inscription with enhanced and reduced resultant chirp.

$$\lambda_B(z) = n_{eff}(z)\cdot\Lambda_{PM}(z) = 2\cdot n_{eff}(z)\cdot\Lambda(z) \quad (2)$$

where both effective refractive index of the fiber core $n_{eff}(z)$ and grating period $\Lambda(z)$ varies with z, while $\Lambda_{PM}(z)$ denotes the phase mask period.

The idea of TCFBG inscription is shown in Fig. 1. When the chirped fiber Bragg grating is written in the rightward taper transition, both $n_{eff}(z)$ and $\Lambda(z)$ increase towards the larger taper diameter (right taper end). Thus, as shown in Fig. 1, the effect of chirp enhancement occurs due to the constructive synthesis of chirps resulting from co-directional increases of fiber diameter and grating period. In this way, a tapered chirped fiber Bragg grating with broadband reflected spectrum $\Delta\lambda_E$ is obtained.

On the other hand, when grating is written in the leftward taper transition, the directions of $n_{eff}(z)$ and $\Lambda(z)$ growth are opposite. Thus, in this case of counter-directional increases of taper diameter and grating period, a mutual reduction of chirps occurs, and resultant spectral width $\Delta\lambda_R$ of TCFBG is significantly narrowed. In conclusion, depending on the phase mask – optical fiber taper configuration used during grating inscription, spectral width adjustment of relatively wide range is possible, where effects of chirp enhancement and chirp reduction caused by the variable-taper profile may be utilized.

Aforementioned spectral width of resulted TCFBG, as a difference between the local Bragg wavelengths $\lambda_B(0)$, $\lambda_B(L)$