Optik 141 (2017) 24–31

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

A two-step scanning-mask exposure method for the fabrication of arbitrary apodized fiber gratings

Tian Kai [a,*], Chen Gen-Xiang [b], Song Qiu-Yan [a]

[a] *School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, China*
[b] *College of Science, Minzu University of China, Beijing 100081, China*

ARTICLE INFO

Article history:
Received 5 December 2016
Received in revised form 15 May 2017
Accepted 19 May 2017

Keywords:
Fiber bragg gratings
Apodization
Optical fabrication
Optical sensing and sensors

ABSTRACT

A novel two-step exposure method for the fabrication of apodized fiber Bragg gratings (AFBG's) with arbitrary apodization functions has been proposed in this paper. The method can be fulfilled by two-step exposures with specially designed apodization and compensation masks for each step, respectively. The masks were driven by a motor which was program controlled according to the desired apodization function. For the sake of validation, three types of AFBG's, with Linear, Gaussian, and Nuttall apodization functions, respectively, have been experimentally fabricated using the proposed method, and the effects of some unideal experimental setups on the reflection spectra of the FBG's were analyzed and discussed.

1. Introduction

Fiber Bragg gratings (FBG's) have many important applications in multi-parameter and multi-channel distributed fiber sensing systems [1–4]. In most cases, the multiplicity and the accuracy of a FBG sensing system are determined by the bandwidth and side lobe suppression ratio (SLSR) of the fiber gratings used in the system. In the past years, many theoretical and experimental efforts have been paid to improving the reflective spectrum shapes of the fiber gratings via apodization techniques [5–10]. In Ref. [8,9], the optical properties of various apodized fiber gratings, with Blackman, Raised Cosine, Singh, Gaussian, and Nuttall apodization functions, were theoretically analyzed in details. Meanwhile, several methods have been proposed for the fabrication of apodized fiber Bragg gratings, such as apodized phase mask method [11], coherent writing method [12], beam scanning method [13,14], point-by-point method [15], special amplitude mask method [16,17]. However, each of these methods has certain limitations. For the apodized phase mask method, not only the fabrication of the phase mask needs very high accuracy which leads to high cost, but also the phase mask has to be customized for a specific grating design. The coherent writing method demands high coherence ultraviolet light source and the apodization function is limited to Gaussian. Both of the beam scanning method and the point-by-point method require highly precise spot-size and position control. For the special amplitude mask method, different amplitude masks are required for different apodization functions. Furthermore, almost all methods are required to adjust the average refractive index using synchronize or secondary compensation exposure to obtain near-ideal apodization functions, except for the apodization phase mask method.

* Corresponding author.
E-mail address: tiank_bjtu@126.com (K. Tian).

http://dx.doi.org/10.1016/j.ijleo.2017.05.064

Table 1
Apodizaton Functions.

Name	Function	Parameters
Uniform	$A(z) = 1 \quad -\frac{Z_g}{2} < z < \frac{Z_g}{2}$	
Line	$A(z) = \begin{cases} \frac{2}{a}\left(z + \frac{Z_g}{2} - a\right) & z < -Z_g 2 + a \\ 1 & \lvert z\rvert < -\frac{Z_g}{2} + a \\ \frac{2}{a}\left(z - \frac{Z_g}{2} + a\right) & z > \frac{Z_g}{2} - a \end{cases}$	$a \in \left(0, \frac{Z_g}{2}\right]$
Gaussian	$A(z) = \exp\left[-\frac{z^2}{(bZ_g)^2}\right] \quad -\frac{Z_g}{2} < z < \frac{Z_g}{2}$	$b \in (0.1, 1]$
Nuttall [7]	$A(z) = a_0 - a_1 \cos\left[2\pi\left(\frac{z - \frac{Z_g}{2}}{Z_g}\right)\right] + a_2 \cos\left[4\pi\left(\frac{z - \frac{Z_g}{2}}{Z_g}\right)\right] - a_3 \cos\left[6\pi\left(\frac{z - \frac{Z_g}{2}}{Z_g}\right)\right] \quad -\frac{Z_g}{2} < z < \frac{Z_g}{2}$	$a_0 = 0.3635819$, $a_1 = 0.4891775$, $a_2 = 0.1365995$, $a_3 = 0.0106411$

The aim of this paper is to propose and implement a novel fabrication method which can fabricate arbitrary AFBG's with highly flexibility. This method mainly includes two steps. The first step is for creating an intensity modulation which has tapered index modulation to achieve the desired apodization, and the second step is for removing the sharp edges of average index modulation. Two specially designed amplitude masks, one is for the apodizaion in the first step and another is for average compensation in the second step, are utilized to control the exposure dose along the grating length through scanning the masks which are driven by motors according to the apodization function. Compared with the fabrication methods mentioned above, this method can make arbitrary AFBG's by using one uniform mask and a simple set of amplitude masks with lower cost, easier control and independent of the coherence of the light source.

The paper is organized as follows: In Section 2, the basic theoretical backgrounds of the two-step exposure method are given, and the optical properties of some typical AFBG's after each exposure step are analyzed for ideal-, under-, over-compensation conditions. In Section 3, experiment setup and the control principle of apodization fabrication of the two-step method are described in details. In Section 4, the experimental results for AFBG's (Linear, Gaussian, and Nuttall) using the proposed method are represented, and some uncertainties are discussed. Finally, conclusions are drawn in Section 5.

2. Theoretical aspects of the two-step exposure method

For the AFBG's fabricated using two step method, the core index variation along the z direction can be generally described as

$$\Delta n(z) = A(z)\,\Delta n_{eff}\left[1 + v\cos\left(\frac{2\pi}{\Lambda}z + \Theta(z)\right)\right] + mB(z)\,\Delta n_{comp}, \quad (-Z_g/2 \le z \le Z_g/2) \qquad (1)$$

The first term in Eq. (1) indicates the index changes introduced by the first step and the second term is the DC compensation of the index changes produced by the second step. A is the apodization function, $\Delta n_{eff}$the effective refractive index variation, v the fringe visibility of the index change, Λ the grating period, Θ the period chirp, m the compensation coefficient, B the compensate function, $\Delta n_{comp}$the compensation of refractive index, and Z_g the length of the grating. Ideally, $A(z) + B(z) = 1$and $m = 1$, $\Delta n_{eff} = \Delta n_{comp}$. In this paper, we set $\Theta(z) = 0$ for clearly description.

In this paper, three typical AFBG's listed in Table 1 are selected as the research objects. The index modulation after each exposure step are illustrated in Fig. 1. For an AFBG with giving index modulation, the optical properties of AFBG's can be numerically calculated using the coupled-mode theory (CMT) and the transfer matrix method (TMM). Fig. 2. shows the calculated reflection spectra of the various gratings after the first (Fig. 2(a)) and second (Fig. 2(b)) exposure step, which shows that after the first step only the side lobe on the red side can be suppressed, and the side lobes both on blue and red side are suppressed significantly after the second compensation exposure step in the ideal situation.

In actual situation, it is not easy to achieve fully compensation due to some uncertainty in the experiment. In Eq. (1), we use compensation coefficient m to indicate the compensation level. Fig. 3 shows the effects of compensation coefficient on the side lobes suppression for Gaussian AFBGs with grating length 10 mm and peak reflectivity 90%. From Fig. 3(a), one can see that the departure of m from its ideal value ($m = 1$) will lead to an asymmetrical side lobes suppression. For $m > 1$, the blue side mode suppression ratio (B-SMSR) can be significantly suppressed, but the red side mode suppression ratio (R-SMSR) will become worse rapidly. The situation is just the opposite for $m < 1$. We can get optimum apodization effect that B-SMSR equals R-SMSR when the value of m is 1. This figure also shows that the two-step exposure method has a certain degree of compensation tolerance. When m falls in the range between *0.8* to *1.2*, both the B-SMSR and the R-SMSR will be better than 30 dB. Fig. 3(b) shows the simulations of reflective spectra for $m = 0$ (before-compensation), *0.8* (under-compensation),