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# Effect of friction in ferrules on compression tuning characteristics of fiber Bragg gratings

Ling Zhao[a,*], Quan Zheng[a], Jianxin Geng[b], Zujie Fang[b]

[a] *Changchun Institute of Optics, Fine Mechanics and Physics, CAS, Changchun 130022, People's Republic of China*
[b] *Shanghai Institute of Optics and Fine Mechanics, CAS, Shanghai 201800, People's Republic of China*

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**Abstract**

The effect of friction in ferrules on compression tuning characteristics of fiber Bragg gratings (FBG) was observed and analyzed in this paper. It was demonstrated that the micro-bending of the fiber in the ferrule would cause friction between fiber and inner wall of the ferrule, and the friction would make a non-uniform strain in the FBG and degradations of its reflection spectrum. To avoid the effect, some measures have been applied including reducing the ferrule diameter to fit the fiber, and filling some lubrication in the ferrule, and so on. Near 10 nm tuning range can be obtained with good spectral performance.


*Keywords:* Fiber Bragg grating; Compression strain tuning; Friction effect

## 1. Introduction

Fiber Bragg gratings (FBG) have obtained more and more applications in optical communications and fiber sensors. Due to the inherent sensitivity to strains of the FBG, mechanical stresses can be used to tune its peak wavelengths. Such tuning techniques have been used in tunable filters for dense wavelength-division multiplexing (DWDM), in tunable fiber lasers, in fiber sensing and other applications [1–4]. Because silica is 23 times stronger under compression than under tension [5], tuning of FBG by compression has shown much wider wavelength ranges than by stretching. Ball and Morey [6] demonstrated a tunable fiber laser with 36 nm of tuning range using compression tuning. A wide tuning range of 45 nm and a fast tuning rate of 21 nm/ms was demonstrated by using compressive tuning [7]. However, there exists changes in spectral profile during the compressive tuning and the phenomenon has not been explained. For compressing a fiber, it is important to keep the fiber straight in its axis and to prevent the FBG from buckling. Generally, the FBG is protected by guiding mechanism, such as a ferrule or composed ferrules. However, there exists some micro-bending in compression because the internal diameter of the ferrule cannot be made absolutely equal to that of fiber. Therefore, a non-uniform distributed friction between ferrule and fiber will result from the micro-bending, which would affect the period of the grating and the tuning spectrum of FBG at last. In this paper, we reported the experimental results of FBG compression tuning and analyzed the effect of friction on its spectral characteristics.

## 2. Experiments

The fiber used for FBG was SMF-28 fiber, whose diameter and length were 125 μm and 1 cm, respectively. Since the anti-compression strength of silica fiber is much larger than its anti-stretch strength, compression strain is more often used in FBG tuning. But a compressed fiber is usually in a sub-stationary status. It is easy for the fiber to bent in compression. According to the mechanics, there is a critical point at which the axial compression state will transform to a bent state. The critical strain is very small [8]. To prevent a compressed fiber from bending, a tight confinement is necessary. In the experiments tiny stainless tubes with an inner diameter of around 300 μm were used as ferrule, in which fiber grating could be compressed or stretched axially. The typical length of the ferrule used in the experiments was about 2 cm, which was needed for packaging.

* Corresponding author. Tel.: +86-431-5601297; fax: +86-21-5958183.
*E-mail address:* lingzhaook@sina.com.cn (L. Zhao).

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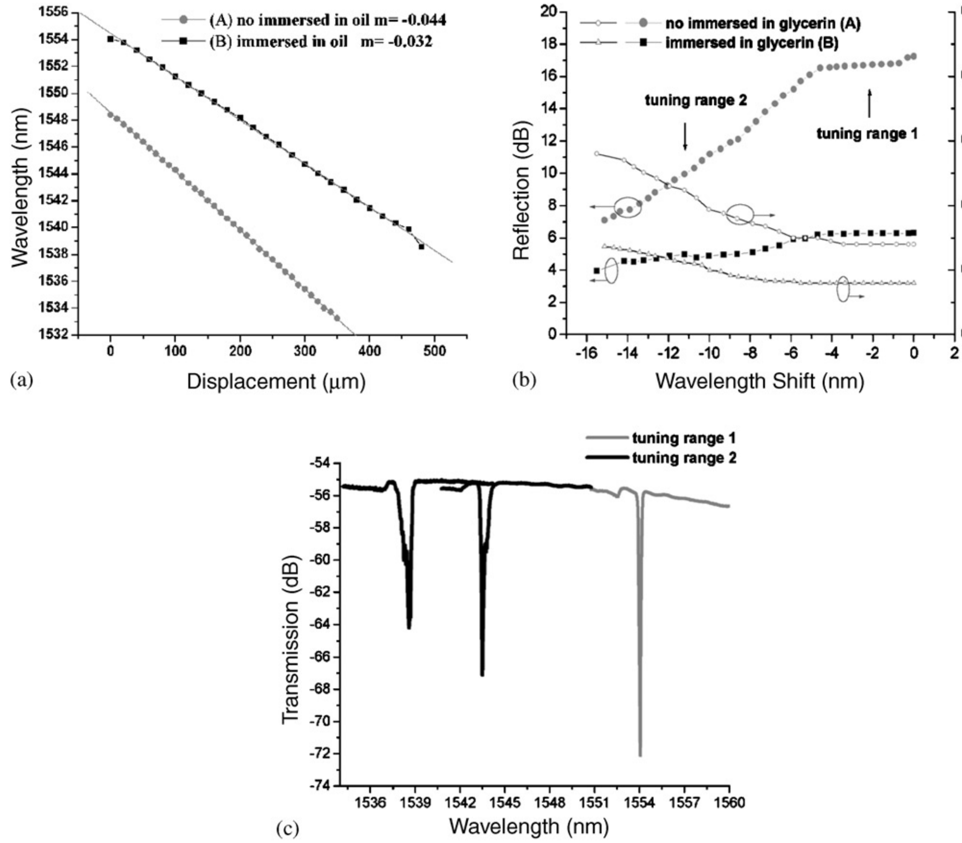


Fig. 1. The results of compression tuning: (a) center wavelength shift versus motor displacement; (b) evolutions of the 3 dB bandwidth and the peak amplitude; (c) transmission spectra in two tuning ranges.

A motor actuator was applied to accurately move one end of the fiber grating while the other end fixed. The inner surface of the stainless tube was carefully polished. To investigate the effect of friction between fiber and the ferrule, two experiments were carried: one was with a glycerin-filled tube to reduce the friction while the other was with an empty tube. The glycerin acted as a lubricant. The length of FBG and ferrule, the diameter of ferrule and the denseness of lubricant would effect the location of FBG inside the ferrule.

The transmission spectra were measured with compression increasing. Fig. 1(a) showed the peak wavelength shift versus fiber end displacement. Because the total lengths of packaged fibers were not the same, there were a little difference in the tuning rates over end displacement: $-0.032$ and $-0.044$ nm/μm, respectively. More than 15 nm tuning range was measured, and linear relations were obtained. The transmission spectrum profile of the tuned FBG was almost the same as that of the un-tuned at the beginning of compression. But the spectral performances were degraded when the tuning range got larger. We defined the tuning range without spectrum changes as ‘tuning range 1’ and that with changes as ‘tuning range 2’, as shown in Fig. 1 (b). It was clear that the evolution of reflection and 3 dB bandwidth was less evident when the fiber was immersed in lubricant. We also measured the transmission spectrum by spectrometer with the resolution of 0.07 nm during ‘tuning range 1’ and ‘tuning range 2’, as shown in Fig. 1 (c). It was found that the reflection peak was hardly changed during ‘tuning range 1’ while there were some sub-structures appeared in long or short wavelength direction of Bragg reflection during ‘tuning range 2’.

## 3. Analysis and discussions

The experimental results lead a speculation of the fiber situation under compression. The fiber was compressed axially inside the ferrule at beginning, and then some micro-bending occurred. The fiber would touch the wall of the ferrule and friction between them would occur. This friction would be in a direction opposite to the applied force and result in retardation of the stress. Let us analyze the stress distribution with friction taken into account. Because the ferrule diameter is quite small, the fiber bending is slight. The main effect to the FBG is still the longitudinal stress. By using a model of elastic rod, the local strain can be expressed as [9]

$$\varepsilon = \partial u/\partial z = u'_z, \tag{1}$$

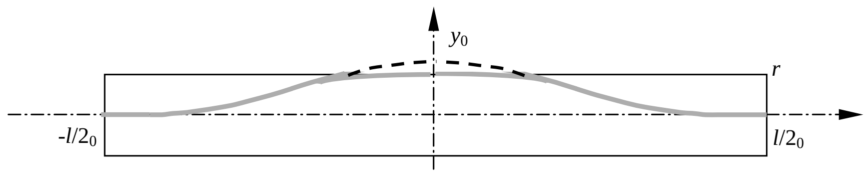


Fig. 2. A schematic diagram of a bent fiber in side a ferrule (dashed line is for free bending case).

where $u$ is the displacement of every point of fiber in $z$ direction. Forces applied on each element section of the fiber include stresses given by its neighboring sections and the friction given by the ferrule wall. Its movement should obey the following equation [9]

$$\rho u''_{tt} = E u''_{zz} - f(z)/s, \tag{2}$$

where $E$ is Young module, $s$ is the area of cross section, $\rho$ is the density, and $f(z)$ is the friction of unit length. In stationary case, the strain distribution can be expressed as a function of static friction [9]

$$\varepsilon = \partial u/\partial z = (1/Es)\int f(z)\,\mathrm{d}z + \text{const.} \tag{3}$$

The static friction is proportional to the normal pressure that depends on the fiber bending. At the beginning of compression tuning, the fiber keeps straight and there will be no friction, the strain is uniform along the axis of FBG. By further compression, the fiber can no longer keep straight and will be bent. But it is not a free bending. The transverse amplitude of the bending was limited by the diameter of the ferrule. Then the fiber would be subjected to a transverse pressure and the static friction as well. The pressure was supposed to be proportional to the transverse deformation caused by ferrule confinement. Fig. 2 shows one case of a bent fiber inside the ferrule schematically.

From the mechanism analysis, the profile of the bent fiber should meet some least requirements: (1) At the ends the fiber should keep in the $z$ direction, (2) The total length of the bent fiber should be equal to the length of compressed fiber. In the case of short fiber the curve of free bent fiber can be qualitatively written as

$$y = y_0 \cos(\pi z/l), \tag{4}$$

where $y_0$ can be approximately deduced as follows:

$$l = 2\int_0^{(l-\Delta l)/2} \sqrt{1+(\mathrm{d}y/\mathrm{d}z)^2}\,\mathrm{d}z \approx l - \Delta l + (\pi y_0/2)^2/l. \tag{5}$$

One can get $y_0 \approx 2\sqrt{l\Delta l}/\pi$. The transverse deformation is roughly equal to the difference between free displacement and the radius of the ferrule. Therefore the friction can be written as

$$f(z) = \eta[y_0 \cos(\pi z/l) - r], \tag{6}$$

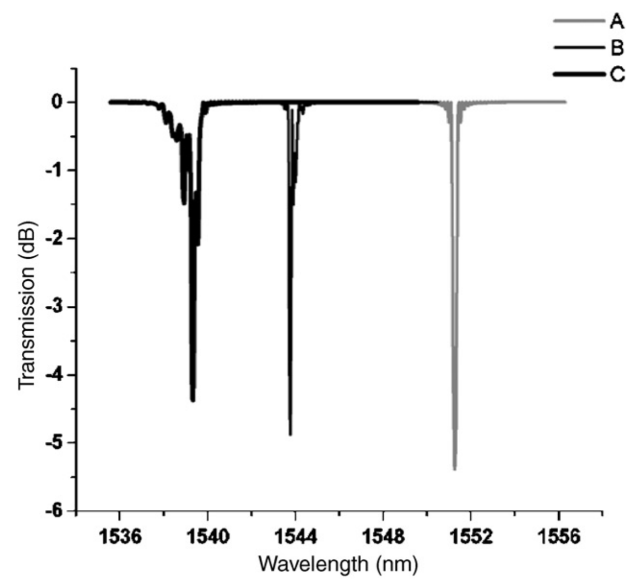


Fig. 3. The simulated transmission spectra corresponding to different friction distributions: (A) symmetric friction; (B) non-symmetric friction centered at near the end with force applied; (C) non-symmetric friction centered at far end with force applied.

where $\eta$ is the coefficient that is proportional to the static friction coefficient, which may be related to the shear module of silica. It is obvious that the effect of friction will be decreased directly by reducing coefficient $\eta$. In the experiment, the filling of lubricant was playing a role of reducing $\eta$.

By using Eq. (6) and the boundary conditions at two ends of the fiber, Eq. (3) can be integrated, so that the distributions of compressed strain and the grating period along the fiber can be obtained. The transmission spectra of the tuned FBG can then be simulated by conventional transmission matrix method for FBG [10], as shown in Fig. 3. The friction also directly depends on the smoothness of the inner wall and the slip guidance of the ferrule. The smoothness in the ferrule is usually not uniform. In Fig. 3, (A) stands for symmetric friction, (B) stands for non-symmetric friction centered at near the end with force applied, and (C) stands for non-symmetric friction centered at far end with force applied. Eq. (6) is for the case of uniform friction coefficient, which may be modified for a non-uniform smoothness of ferrule inner wall. In that cases, the curve of bent fiber may not be symmetric to the middle point of the ferrule, and the two ends may be under different stresses with different lengths, which will lead to a non-symmetric profile of the spectral line. The Bragg period before compressive tuning was 526.95 nm and the effective refractive index was 1.45 during simulation. The static friction coefficient $\eta$ was normalized to 1 and the Bragg grating period where bending existed was equivalent to chirped period with chirp coefficient $10^{-4}$ nm/cm.

To overcome the effect of ferrule friction, the FBG should be prevented from being bent. Obviously, it is important to make the diameter of ferrule fit the fiber as much as possible. The transverse pressure comes from the axial stress and equals to a product of the stress and the tangent of fiber slope angle. Therefore, the transverse pressure will be small in a tight ferrule. The main difficulty for doing so is mainly from the packaging technique. The technical improvements are necessary, and being undertaken.

## 4. Conclusions

The effect of friction in the ferrule on compression tuning of FBG was described and analyzed in this paper. It is indicated that the friction is caused by FBG bending. When the FBG keeps straight under compression, the tuning characteristics are quite normal and satisfactory. When the FBG is bent under larger compression forces, friction between the wall of ferrule and FBG will result in degradation of the spectrum: peak reflection reduced, 3 dB bandwidth increased, and line profile with sub-structure appeared. Simulation indicates that the analysis is reasonable. To alleviate the effect, it is important to make the ferrule smaller to fit the fiber, and to smooth the inner wall of the ferrule by some lubrication to reduce the static friction coefficient.

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