Department of Electrical
and
Computer Systems Engineering

Technical Report
MECSE-24-2004

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Le Nguyen Binh, R. T. Zheng, N. Q. Ngo,
S. C. Tjin and J. L. Yang

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R. T. Zheng, N. Q. Ngo, S. C. Tjin and J. L. Yang

Photonics Research Center

School of Electrical and Electronic Engineering

Nanyang Avenue, Nanyang Technological University. Singapore 639798

Email: EQNNGO@NTU.EDU.SG, Tel: (65) 67904341, Fax: (65) 67920415

Le Nguyen Binh

Laboratory for Optical Communications and Applied Photonics

Department of Electrical and Computer Systems Engineering, Monash University

Clayton Victoria 3168 AUSTRALIA

Abstract: We present the design, fabrication and testing of the piece-wise stepped-chirp fiber Bragg gratings (FBGs) with arbitrary group delay responses using a uniform phase mask under pre-stretched condition. The method involves writing a series of sub-gratings on a pre-stretched fiber whose length is varied during the UV exposure process. Two motorized stages are employed to control the length of the pre-stretched fiber in order to adjust the grating pitch at each writing step to achieve piece-wise stepped chirping of the FBG. Because the fiber is moved relatively to the phase mask, an apodized index modulation profile of the FBG can be obtained by fiber dithering. To demonstrate the effectiveness of the method to produce FBGs with arbitrary group delay responses, a linear-chirp unapodized FBG and a quadratic-chirp apodized FBG were fabricated, and their experimental results agree well with the analytical predictions.

Keywords: Stepped chirp fiber Bragg gratings, uniform phase mask, phase shift, apodization, optical filters, dispersion compensation

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[1] Parts of this report have been published in Optics Communications 2004.

1. INTRODUCTION

Chirped fiber Bragg gratings (CFBG) are gratings with their Bragg wavelengths varying linearly or nonlinearly along the grating length. CFBGs have been widely used for dispersion compensation, pulse multiplication and pulse compression [1-3]. To fabricate CFBGs to tailor for different applications, several techniques have been developed. One method involves the use of a chirped phase mask. However, a chirped phase mask is expensive, and the fabricated gratings always exhibit a fixed group delay characteristics. To overcome this drawback, considerable attempts have been made to fabricate chirped gratings using a less expensive uniform phase mask. These methods are dual-scanning technique [4], shifting the Bragg wavelength by the addition of a converging lens before the mask [5], and moving fiber/phase mask-scanning beam technique [6]. A technique for fabrication of long gratings with complex profiles was developed in [7]. The idea was to expose a large number of small partially overlapping subgratings in sequence by UV pulses. Each subgrating contained a few hundred periods or less. Thus the advanced properties such as chirp, phase shifts, and apodization were introduced by adjusting the phase offset and pitch of the subgratings. Pertermann and his colleagues further improved the method by using continuous wave (CW) UV source and a sawtooth movement of the interference pattern [8]. With this method, the grating period was varied with the interferometric setup. This method requires high position accuracy and they use an interferometric system to monitor the translation stage.

The design of stepped-chirp fiber Bragg gratings has been discussed by Kashyap [9], By using a stepped chirp phase mask, the stepped chirp FBG can be fabricated [10]. Reference [11] presents a stretching and writing technique to fabricate such stepped chirp FBG. In this method, the Bragg wavelength along the grating length can be adjusted by controlling the strain of the fiber during UV exposure compared with method presented in [8], which controlling the interferometric setup. Because the interferometer to inscribe the grating is formed by a uniform phase mask, the exposure process is comparable stable. However, Ref. [11] has not studied the relationship between the group delay response of FBG and the corresponding fabrication parameters, thus tailoring chirped gratings with arbitrary group delay responses is still a challenging problem with this method. Furthermore, the fiber is stretched on one side during writing process in the method presented in [11], so that the fabrication process might take a big phase error to the fabricated grating.

In this paper, we inscribe the step-chirped FBG with an arbitrary group delay response using a uniform phase mask in a pre-stretched fiber. Two motorized stages are employed to adjust the length of the pre-stretched fiber during UV exposure to obtain the fabricated FBG with a desired group delay response. In order to control the phase of the grating continuously, the moved lengths of two motorized stages are dynamically assigned to achieve a desired group delay response. The fiber can be dithered by two stages during exposure process to realize an apodized grating profile. To obtain a constant distribution of strain along the pre-stretched fiber, the coating of the fiber is stripped off before fabrication.

The main improvement of the proposed method over the method presented in [11] is that the proposed method uses two stages to stretch the fiber to ensure a minimized phase error. Furthermore, the coating of the fiber is stripped off while the coating was left in the method presented in [11]. Because the coatings will decrease the UV exposure efficiency, the presented method can produce stronger gratings than those fabricated with the method in [11]. In this paper, a linearly chirped FBG and a nonlinearly-chirped FBG are fabricated using the proposed method. The measured reflective spectra and the group delay responses of the linearly chirped FBG and the nonlinearly chirped FBG are consistent with the analytical predictions.

2. FABRICATION SYSTEM AND ANALYSIS

Fig. 1 shows the schematic diagram of the setup used for fabricating the FBGs with arbitrary group delay responses. The UV beam from a frequency-doubled Argon laser is folded by a mirror mounted on a motorized translation stage and focused using a cylindrical lens onto the pre-stretched fiber through the phase mask. The UV beam is scanned along the pre-stretched fiber and the scanning velocity is controlled by a motorized translation stage. The fiber is clamped by two motorized stages (i.e. Stage A and Stage B). The mounted fiber is then pre-stretched before the UV exposure so that the fiber length can either be increased (by stretching the fiber) or decreased (by releasing the fiber). The plastic coating of the fiber might reduce the exposure efficiency and hence reducing the grating depth. The gratings used for dispersion compensation tend to be strong so the gratings are often inscribed with the coatings stripped off. To obtain a constant distribution of the in-fiber strain along the fiber length, the plastic coating of a segment of the fiber between the two holders is removed including the segment without the inscribed grating. The coating in the segment in the holders is not stripped off to avoid slippage.

The photosensitivity of the fiber could be changed with different in-fiber strain. However, the change of the in-fiber strain is quite small, thus the effect on the photosensitivity of the in-fiber strain can be ignored in our experiments. The original distance between the two stages is L_1 during the UV scanning of the first sub-grating. Before the second sub-grating is written, both ends of the fiber (with length L_1) are stretched and the fiber length now becomes $L_2 = L_1 + x_1$, where x_1 is the amount of stretching on both fiber ends, and $L_2 > L_1$ for $x_1 > 0$ (i.e. stretching the fiber) or $L_2 < L_1$ for $x_1 < 0$ (i.e. releasing the fiber). That is, the stretched length $x_1 = x_A^1 + x_B^1$ is the amount of movement of Stage A and Stage B, where x_A^1 and x_B^1 are the distances moved by Stage A and Stage B, respectively (see Fig. 1). And l_1 is the distance between Stage A and the position between the first sub-grating and the second sub-grating. After the fiber is stretched (or elongated), it is moved relatively to the phase mask. As a result, a phase shift could be inserted between two neighboring sub-gratings. When the moving distances of Stage A and Stage B follow the following relationships

$$x_A^1 = \frac{x_1 l_1}{L_1} \text{ and } x_B^1 = x_1 - x_A^1 = \frac{x_1(L_1 - l_1)}{L_1} \tag{1}$$

then the phase of the grating can be kept continuous (i.e. no phase shift is inserted between neighboring sub-gratings). After the fiber is stretched, the grating period of the first sub-grating will be elongated (i.e. $L_2 > L_1$). Thus the difference in the grating periods between the first sub-grating and the second sub-grating can be described by

$$\Delta\Lambda_1 = \frac{x_1}{2L_1}\Lambda_\mathrm{p} \tag{2}$$

where Λ_p is the period of the phase mask. The index modulation of the grating will be averaged when the UV beam illuminate the fiber in moving. To avoid it, the UV beam will be shielded when the fiber is stretched. Thus a chirped grating fabricated with N steps can be formed after fabricating a number of consecutive sub-gratings with a serious of stretched lengths between any two neighboring sub-gratings as described by $\overrightarrow{X} = \{x_1, x_2, \ldots, x_{N-1}\}$. The variation of the fiber length during stretching is given by $\vec{L} = \{L_1, L_2, \ldots, L_N\}$, where L_i is the fiber length when inscribing the *i*th sub-grating. Assuming that the average fiber length is given by $L_{\text{avg}} = \dfrac{L_1 + L_2 + \cdots + L_N}{N}$ and using the fact that $L_i >> x_i$, we have $L_1 \approx L_2 \approx \cdots \approx L_{\text{avg}}$. The longitudinal position of the *i*th sub-grating along the fiber length is $z_i = i \times \Delta z$, where $i = 1, 2, \ldots, N$, is the section number and Δz is the length of each sub-grating. Thus the Bragg wavelength at position z_i can be approximately given as

$$\lambda(z_i) = \lambda_1 + 2n_{eff} \sum_{k=1}^{i} \Delta\Lambda_k = \lambda_1 + \frac{n_{eff}\Lambda_{\text{p}}}{L_{\text{avg}}} \sum_{j=1}^{\frac{z_i}{\Delta z}-1} \overrightarrow{X}(j) \tag{3}$$

where n_{eff} is the effective index of the grating, and λ_1 is the Bragg wavelength of the first sub-grating which can be determined by the initial strain applied to the fiber. Thus the grating fabricated by the method will have a stepped-chirp grating period as the same characters as presented in [9] [10]. Figure 2 shows the schematic diagram of such kind of stepped-chirp grating.

The time delay of the grating can be calculated by computing the change in phase as a function of wavelength λ_i [9] [12] as given by

$$\tau(\lambda_i) = \frac{\partial\phi}{\partial\omega} = -\frac{\lambda_i^{\,2}}{2\pi c}\frac{\partial\phi}{\partial\lambda} \tag{4}$$

For chirped grating, the phase variation along the grating length z can be obtained by [13]

$$\frac{1}{2}\frac{\partial\phi}{\partial z} = -\frac{4\pi n_{eff} z}{\lambda^2}\frac{d\lambda}{dz} \tag{5}$$

by substituted Eq. (5) into Eq. (4), we can obtain

$$\tau(\lambda_i) = 2n_{eff} z / c \tag{6}$$

where c is the speed of light in vacuum. It should be noted that the distance between Stage A and the exposure position, that is $\vec{l} = \{l_1, l_2, \ldots, l_{N-1}$ where $l_{N-1} > l_2 > l_1$), becomes longer during the exposure process. The stretched lengths

$\overrightarrow{x_A} = \{x_A^1, x_A^2, \cdots, x_A^{N-1}\}$ and $\overrightarrow{x_B} = \{x_B^1, x_B^2, \cdots, x_B^{N-1}\}$ must be dynamically set according to Eq. (1) to obtain a stepped-chirp grating with a continuous phase.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In the experiment, we inscribed the grating onto a germanium-doped fiber (PMS 50 from Stock Yale). The period of the phase mask is 1070 nm. The power of the UV laser is 50 mW. The translation stage we used is Newport PM500-LW (the accuracy is 0.2μm) and the two stages used for stretch the fiber are from Newport either, which have the accuracy of 0.05μm.

First, an unapodized linearly chirped grating was fabricated. To obtain a linearly chirped grating, the different stretched lengths were set to be the same (i.e. $x_1 = x_2 = \ldots = x_{N-1} = x_c$, where x_c is a constant value). For a linearly chirped FBG, the corresponding set of Bragg wavelengths of the sub-gratings along the stretched fiber can be derived from Eq. (3) as

$$\lambda(z_i) = \lambda_1 + \frac{n_{eff}\Lambda_{\mathrm{p}} x_c}{L_{\mathrm{avg}}} \times (\frac{z_i}{\Delta z} - 1) \tag{7}$$

Thus the group delay τ(λ) of a linearly chirped FBG relates to this set of Bragg wavelengths as

$$\tau(\lambda) = \frac{2\Delta z \cdot L_{\mathrm{avg}}}{\Lambda_{\mathrm{p}} x_c c}(\lambda - \lambda_1) + \frac{2n_{eff}\Delta z}{c} \tag{8}$$

The dispersion of a linearly chirped FBG can be derived from Eq. (8) as

$$D = \frac{d\tau}{d\lambda} = \frac{2\Delta z L_{\mathrm{avg}}}{\Lambda_{\mathrm{p}} x_c c} \tag{9}$$

The velocity of the translation stage is 0.01 mm/s. The initial length of the pre-stretched fiber, L_1, between Stage A and Stage B is $L_{\mathrm{avg}} = 193\,\mathrm{mm}$. The number of sub-gratings is 50 and the total length of the FBG is 25 mm. Thus the length of the sub-grating is $\Delta z = 25\,\mathrm{mm}/50 = 0.5\,\mathrm{mm}$. The stretched length profile was set as $\overrightarrow{X}$ ={5, 5, …, 5} μm and thus $x_C = 5\,\mu\mathrm{m}$. Putting these parameter values into Eq. (8), the calculated dispersion of the FBG is 120.25 ps/nm.

Figure 2 shows the measured reflective spectrum and group delay response of the fabricated linearly chirped FBG. The in-band dispersion is ~123.9 ps/nm and is quite close to the theoretical value of 120.25 ps/nm, and Fig. 3 shows the deviation of the linear portion of the group delay. However, there are some ripples in the reflective spectrum shown in Fig. 2, and the largest ripple is ~10 dB at a wavelength of 1552.7 nm. Such ripples are caused by some position errors (i.e. precise control of $\vec{x}_A$ and $\vec{x}_B$) and hence errors in controlling the grating phase.

Second, we applied the method to fabricate an apodized quadratic-chirp FBG. To produce a quadratic chirp profile, the stretched lengths were set as $\overrightarrow{X}(i) = x_1 - k(i-1)$, where i = 1, 2,…, N–1, and k is a constant value. Using Eqs. (3) and (4), we can derive the group delay as a function of the Bragg wavelength of a quadratic chirp FBG as

$$\tau(\lambda) = -\frac{2n_{eff}\Delta z(x_1 + k/2)}{k \cdot c}\left[1 - \frac{2kL_{\text{avg}}}{n_{eff}\Lambda_{\text{p}}(x_1 + k/2)^2}(\lambda - \lambda_1)\right]^{1/2} + C \tag{10}$$

where C is a constant. If Eq. (10) is expanded in a Taylor series, we can obtain

$$\tau(\lambda) = \tau(\lambda_1) + \frac{2\Delta z L_{\text{avg}}}{c\Lambda_{\text{p}}(x_1 + k/2)}(\lambda - \lambda_1) + \frac{1}{2!}\cdot\left(\frac{kL_{\text{avg}}^2}{2n_{eff}\Lambda_{\text{p}}^2 c(x_1 + k/2)^3}\right)\cdot(\lambda - \lambda_1)^2 + \ldots \tag{11}$$

The velocity of the translation stage is 0.005 mm/s. The initial length of the pre-stretched fiber, L_1, between Stage A and Stage B is $L_{\text{avg}} = 193\,\text{mm}$. The number of sub-gratings is 100, the total length of the FBG is 50 mm and hence $\Delta z = 50\,\text{mm}/100 = 0.5\,\text{mm}$. The stretched length of the ith section was set as $x(i) = x_1 - 0.029(i-1)$ µm where i = 1, 2,…, N–1. Putting these parameter values into Eq. (10), the calculated linear coefficient of the time delay is 164.1 ps/nm and the quadratic coefficient (or dispersion slope) is 21.3 ps/nm^2.

Figure 4 shows the measured reflectivity spectrum and the group delay response of the quadratic-chirp FBG. Figure 5 shows the quadratic part of the measured in-band group delay response (i.e. linear portion of the GD has been substracted), and the estimated linear coefficient is 158.9 ps/nm and the quadratic coefficient is 19.7 ps/nm^2.

As described above, the large ripples in the reflective spectra of both the linearly chirped FBG and the quadratic chirp FBG are probably due to the position errors (i.e. precise control of $\vec{x}_A$ and $\vec{x}_B$) and hence the errors in controlling the phases of the two FBGs. This problem could be overcome by using more precise controllers such as PZT controllers instead of the motorized stages (i.e. Stage A and Stage B) presented here.

The main limitation of the presented method is the bandwidth of the grating fabricated. It is mainly determined by the material of the fiber. Ref. [13] has reported the gratings fabricated using polymer fiber has a tunable wavelength range around 20 nm. However, with increasing of the bandwidth of the fabricated grating, the strain of the fiber will increase during fabrication. As a result, the fabrication process has a higher requirement for the position devices which holds the fiber.

4. CONCLUSION

We have presented the design and fabrication of the piece-wise stepped-chirp fiber Bragg gratings (FBGs) written using a uniform phase mask under pre-stretched condition to produce FBGs with arbitrary group delay responses. The group delay response can be arbitrarily obtained by setting the stretched length of the fiber during UV exposure to introduce the phase shifts into the FBG to realize the apodized index modulation profile. An unapodized linearly chirped FBG and an apodized quadratic chirp FBG were fabricated using this method. The measured group delay responses of these two types of FBGs show a good agreement with the analytical predictions.

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Figure Options

Fig. 1 Schematic diagram of the system setup for fabricating the chirped FBG with arbitrary group delay responses.

Fig. 2 Schematic of a step-chirped grating, showing N equal sections of δl each with a different period [10]

Fig. 3 Measured reflective spectrum and group delay response of a linearly chirped FBG.

Fig. 4 Deviation of the linear time delay of the measured in-band group delay response. The estimated dispersion factor is 123.9 ps/nm.

Fig. 5 Measured reflective spectrum and group delay response of a quadratic chirp FBG.

Fig. 6 Deviation of the linear time delay of the measured in-band group delay response of a quadratic chirp FBG. The estimated dispersion is 158.9 ps/nm and the estimated dispersion slope is 19.7 ps/nm^2.

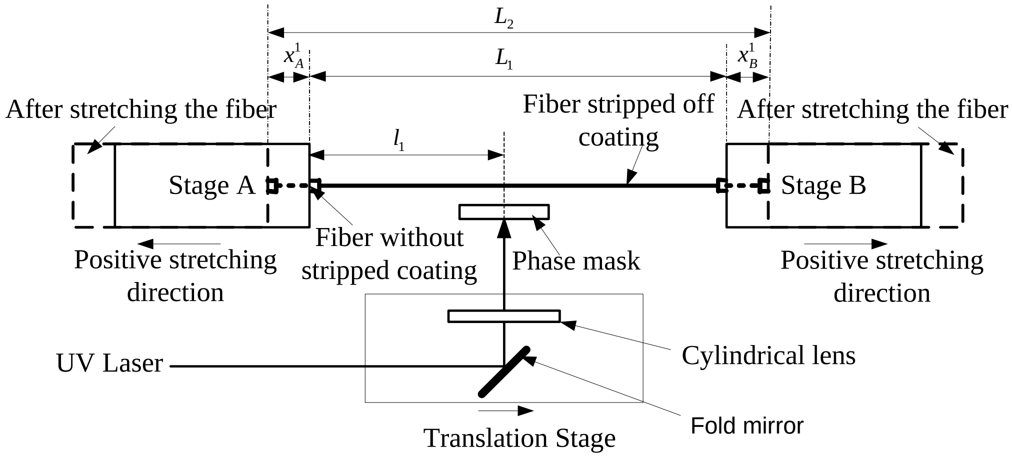


Fig. 1

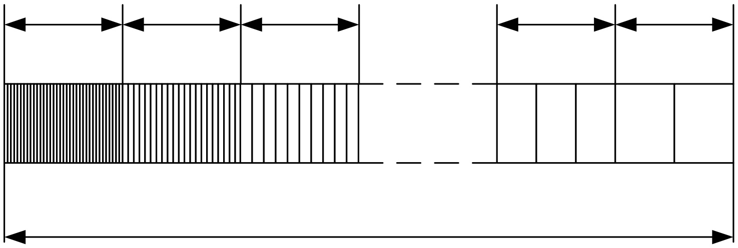
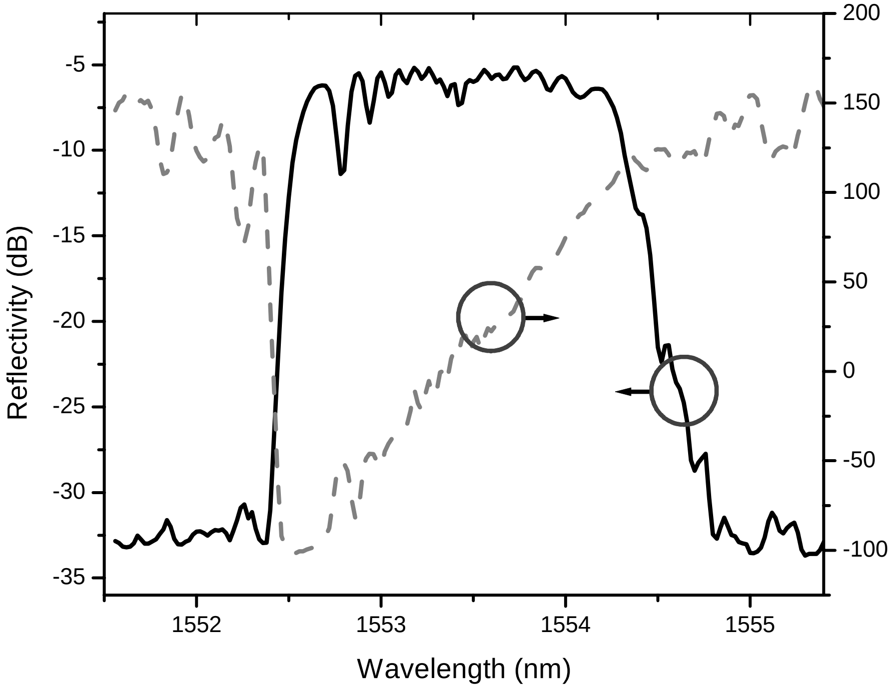


Fig. 2

δl



Λ_1

Fig. 3

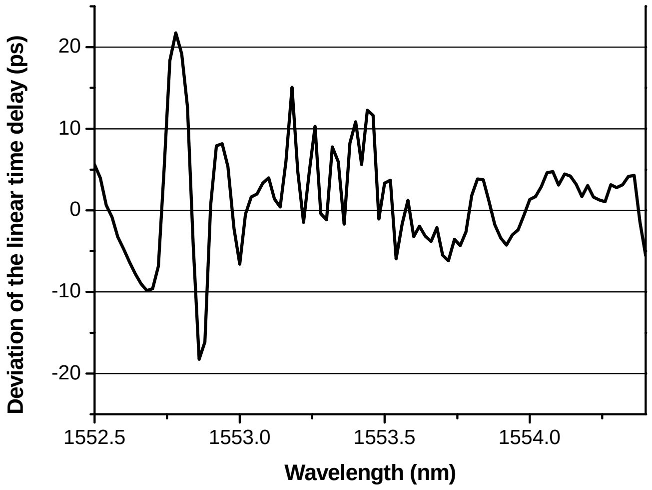

Deviation of the linear time delay (ps)
20
10
0
-10
-20
1552.5
1553.0
1553.5
1554.0
Wavelength (nm)

Fig. 4

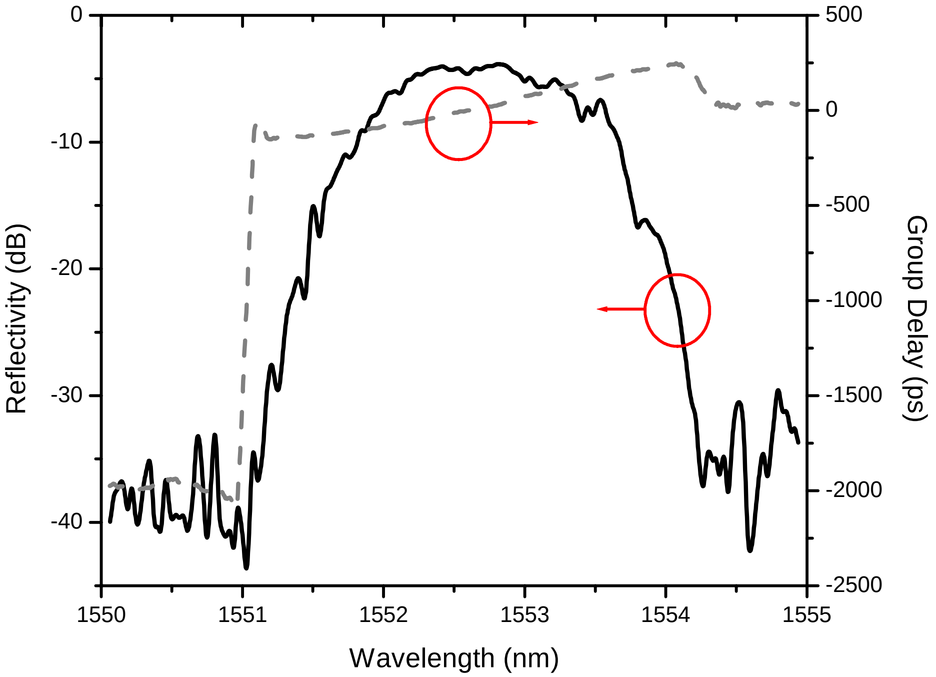

Reflectivity (dB)
0
-10
-20
-30
-40
Group Delay (ps)
500
0
-500
-1000
-1500
-2000
-2500
1550
1551
1552
1553
1554
1555
Wavelength (nm)

Fig. 5

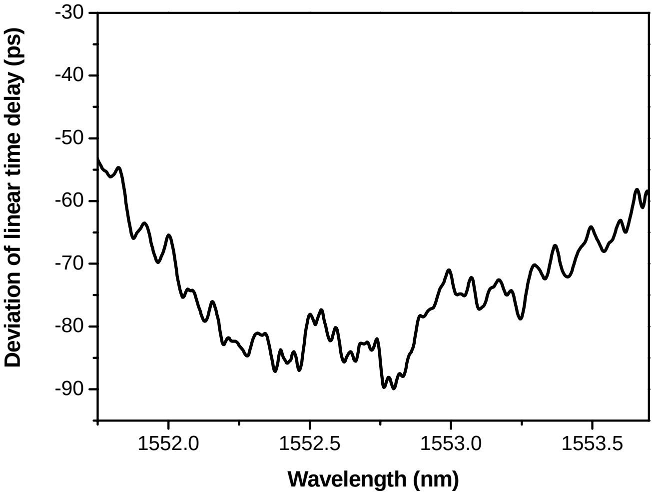

-30
-40
-50
-60
-70
-80
-90
Deviation of linear time delay (ps)
1552.0
1552.5
1553.0
1553.5
Wavelength (nm)

Fig. 6