# Chirped and phase-sampled fiber Bragg grating for tunable DBR fiber laser

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**Abstract:** Chirped and phase-sampled fiber Bragg gratings are fabricated and used as reflectors in tunable DBR fiber laser for the first time. By controlling the phase of each sampling section, sampled Bragg gratings (SBG) with different channel spacing can be obtained using only a single chirped phase mask. A 30nm-wide tunable Erbium-doped fiber (EDF) laser is designed and experimentally demonstrated by utilizing the vernier effect of two such SBGs with channel spacing of 3.2nm and 3.6nm, respectively. The lasers' output power of different channels is almost identical (difference less than 1dB) within the tunable range.



**OCIS codes:** (050.2770) Gratings; (050.5080) Phase shift; (140.3510) Lasers, fiber; (140.3600) Lasers, tunable

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## 1. Introduction

Widely tunable fiber lasers are very attractive for DWDM systems and fiber sensors for their low cost, narrow linewidth and low lasing threshold. Sampled Bragg gratings (SBG) have been widely used as the reflectors in external cavity tunable DBR fiber laser [1-4]. As shown in Fig. 1, two multi-channel SBGs with slightly different channel spacing will lead to vernier effect in their reflection spectra. When only one SBG is being turned, just a single pair of channels in the two SBGs will overlap, and lasing will occur at the wavelength of that channel. However, in order to improve the performance of such tunable fiber lasers, multi-channel SBGs with larger channel spacing, wider total bandwidth and nearly identical spectrum response among channels are required. Assume that the average channel spacing in

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the two SBGs is $\Delta\lambda_s$ and the difference in channel spacing between the two SBGs is $\Delta\lambda_0$, then when only one SBG is tuned, the maximum number of lasing wavelengths achievable is about $\Delta\lambda_s/\Delta\lambda_0$ and the maximum tunable range of the laser is $\Delta\lambda_s^2/\Delta\lambda_0$. In general, $\Delta\lambda_0$ can't be very small and it must be larger than the 10dB-bandwidth of the reflection peak in each channel. Hence, in order to broaden the laser's tunable range, SBGs with larger channel spacing and wider total bandwidth are desired. Obviously, in order to obtain nearly identical output spectrum for all lasing wavelengths, all reflection peaks in each SBG should be almost identical.

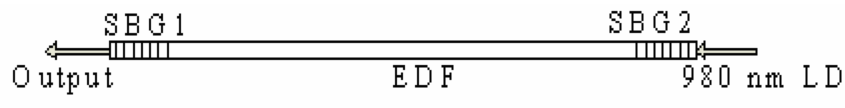


Fig. 1 Structure of DBR tunable fiber laser

However, such kind of SBG is a challenge for conventional grating fabrication techniques. Under the condition of weak refractive index modulation, the grating spectrum can be predicted as Fourier transform of the index modulation. For SBGs, the reflection spectral envelope is determined by the shape of an individual grating sample. To achieve wide total bandwidth and large channel spacing, both the duty circle of each sample and the sampling period must be small enough. Consequently, the samples must be very short indeed, which needs higher precision in fabrication. Further more, in order to ensure identical spectral response among all channels, the apodization of individual samples must be carefully crafted following a sinc function [5]. This is not easily achieved with readily available laboratory grating writing technology. Especially, the fabrication difficulty increases with larger channel spacing.

Strongly chirped SBGs have been proposed [6] to partially meet this challenge. Chirped grating has the effect of placing the spectral center of each sample at a different wavelength, thus reducing the width of the spectral envelope required and relaxing the strict length requirement on each sample. Meanwhile, such strongly chirped SBGs based on on/off sampling function are relatively easy to fabricate. The performance of each channel is almost identical within the total bandwidth when the chirp coefficient matches with the sampling period. However, according to the phase matching condition, only some particular channel spacing can be obtained under a given chirp coefficient, hence different chirped phase masks must be used to fabricate such SBGs, which is inflexible to produce reflectors with different channel spacing for tunable fiber lasers.

Recently, we have proposed a chirped SBG with phase shift for high channel-count comb filter for DWDM systems [7]. Modifications of this chirped and phase-sampled fiber Bragg grating (FBG) are made for tunable fiber lasers demonstrated in this paper. SBGs with different channel spacing are obtained using only a single chirped phase mask. By using two of these novel SBGs with channel spacing of 3.2nm and 3.6nm, respectively, a 30nm-wide tunable Erbium-doped fiber (EDF) laser with almost identical output power for each lasing wavelength has been achieved.

## 2. Design method of chirped and phase-sampled FBG

Along the length of a chirped SBG, phase shift $\varphi_k$ is introduced between the $k_{th}$ and $(k+1)_{th}$ sample, where

$$\varphi_k = k\varphi, \qquad k = 1,2,3,\ldots n-1 \tag{1}$$

is proportional to k, and n is the total amount of samples. In order to get a Talbot-like spectral response [7], chirp coefficient C, sampling period P and $\varphi$ should obey the following phase matching condition:

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$$\varphi + \frac{2\pi C}{\Lambda_0^{\ 2}} P^2 = \frac{2\pi}{N} \tag{2}$$

where $\Lambda_0$ is the center grating period and N is an arbitrary positive integer. Then, the reflection spectrum will be multi-channel, with identical response within a certain bandwidth, just similar to the reflection spectrum in a comb filter. Meanwhile, the adjacent channel spacing $\Delta\lambda$ is

$$\Delta\lambda = \frac{2n_{eff}\Lambda_0^{\ 2}}{NP} \tag{3}$$

*where $n_{eff}$ is the effective core index.*

After introducing the phase shifts $\{\varphi_k\}$ into chirped SBGs, comb filters with different $\Delta\lambda$ can be designed with a given phase mask by determining P and $\varphi$ (the two most important parameters to fabricate the required SBG) through Eqs. (3) and (2), respectively. A simulation result is shown in Fig. 2, wherein refractive index modulation amplitude $\Delta n=2\times10^{-4}$, grating length L=5cm, C=2.7nm/cm, $\Lambda_0$=532nm, $n_{eff}$=1.455, N=1, and $\Delta\lambda$=3.2nm. In the simulation, an on/off sampling function for each sample is used to design this SBG, and the duty circle is 50%. So, conventional grating writing technology can meet the fabrication requirement of this SBG. Using the same chirp coefficient C, SBGs with different channel spacing can be designed.

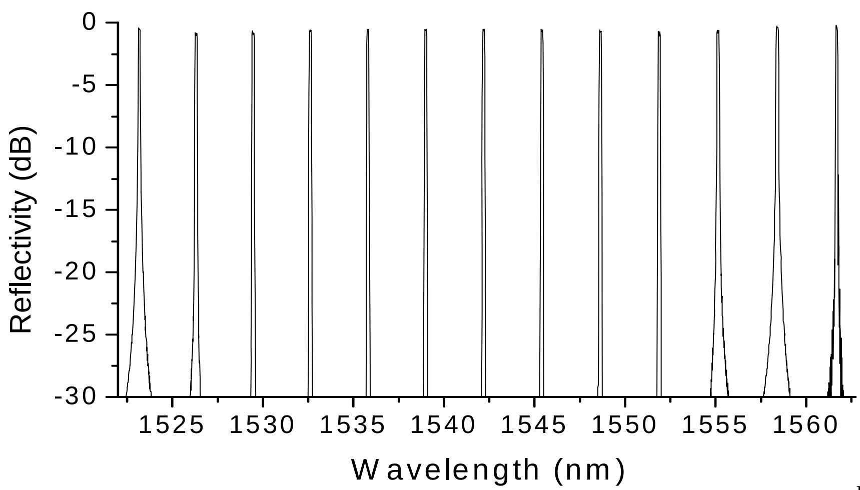


Fig. 2 Simulated reflection spectrum of an SBG. Parameters see text.

As shown in Fig. 2, the spectral response of all channels keeps almost identical over more than 40nm bandwidth. Since the total bandwidth is proportional to C and L [7], more channel count can be easily obtained by increasing the length of the SBG. However, such characteristics are difficult to achieve by conventional on/off SBGs, especially when $\Delta\lambda$ and channel count M are quite large, which requires smaller P (proportional to $\Delta\lambda^{-1}$), lower duty circle (proportional to $M^{-1}$) and larger index modulation (proportional to M). On the other hand, such SBGs can be fabricated easily with the method proposed in this letter with conventional grating writing technology. Meanwhile, because the spatial interval between the neighboring phase shifts equals to the sampling period (in the order of $10^{-1}$ mm), it is possible to control the phase of each sample precisely by moving the phase mask during the process of grating fabrication. Compared with sinc-sampled method requiring precise apodization and phase shifts, the present technology is less expensive and more flexible. In other word, the

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proposed fabrication method of this phase-sampled chirped FBG has many advantages over the existed techniques.

### 3. Experimental results and discussion

The SBGs are fabricated by the standard scan-writing technology with a frequency-doubled Argon laser. The phase mask is fixed on the top of a translation stage driven by piezoelectric (PZT) ceramic with a nominal moving precision of 5nm, and the phase shifts in the SBG are obtained by moving the phase mask [8].

The challenge in the fabrication is to precisely control the phase shifts. According to simulation analysis, the deviation of the phase shifts must be less than 10%. For example, to obtain a $\pi$-shift, the phase mask will be shifted about $0.5\Lambda_0 \approx 250$nm. Then the maximum tolerance in translation is about 25nm. Although the translation stage we used has a nominal precision of 5nm, such a tiny displacement may be disturbed by many factors such as the noise of PZT ceramic's driving voltage, the relative location of the fiber and phase mask, etc. In our experiment, we found that all of these effects lead to a linear deviation of the actual displacement of the phase mask. So the supposed displacement of the translation stage is multiplied by a factor directly obtained from the experiment in order to compensate for the errors.

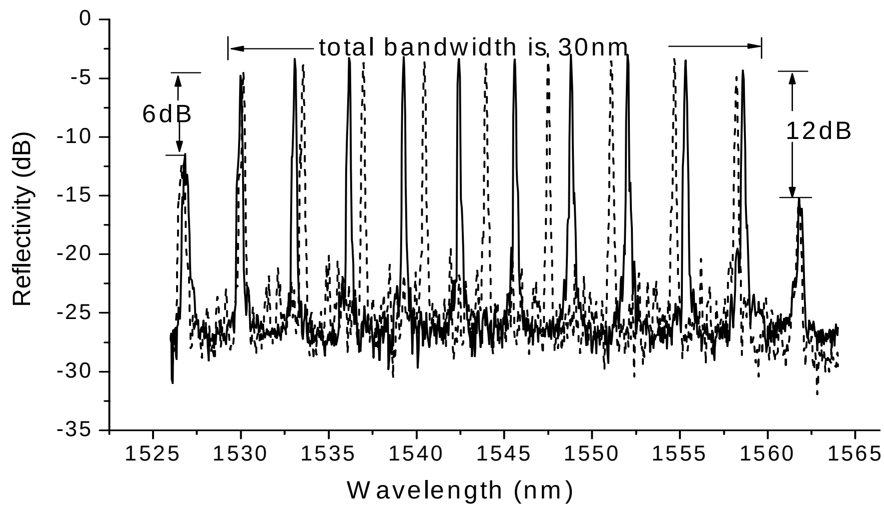


Fig. 3 Measured reflection spectrum of SBGs with $\Delta\lambda$=3.2nm, P=0.256mm, $\varphi$=1.879$\pi$ (solid curve); and $\Delta\lambda$=3.6nm, P=0.228mm, $\varphi$=1.905$\pi$ (dashed curve).

Two SBGs with $\Delta\lambda$=3.2nm and 3.6nm are fabricated with a single chirped phase mask (length=44mm, chirp rate=5.19nm/cm). Their reflection responses are measured by an optical spectrum analyzer and shown in Fig. 3. The fabrication parameters include: $\Lambda_0$=531.4nm, C=2.60nm/cm, N=1, $n_{eff}$=1.451, L=4.2mm, and $\Delta n \approx 1.5\times10^{-4}$. The dimension of the UV laser beam parallel to the fiber is about 0.15mm, which makes the minimum sampling period of 0.2mm realizable.

From Fig. 3 one can see that the reflection spectra of all channels are almost identical (peak difference less then 1dB) over a bandwidth as wide as around 30nm, and the peak reflectivity within the band is at least 6 dB higher than those out of the band. For the tunable fiber laser, this will result in identical spectral response among all lasing wavelengths within the band, while no lasing will occur out of the band.

Figure. 3 also shows the vernier effect in the spectra caused by the difference in the channel spacing (0.4nm) of the two SBGs. Using these two SBGs as reflectors and a 4m-long EDF as the gain medium with absorption coefficient of 5dB/m at 980nm, an external cavity tunable DBR fiber laser is formed (see Fig. 1). By tuning the center wavelength of one SBG

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continuously and holding the other one constant, only one channel from each of the two SBGs will experience vernier enhancement due to channel overlapping.

The tuning result of the fiber laser is shown in Fig. 4. When only one SBG is tuned continuously, lasing occurs at 9 different wavelengths one after one, and the output power (~ -3 dbm) for each wavelength is almost identical (difference less than 1dB). If both SBGs are tuned, the lasing wavelength can be tuned continuously over 30nm. The maximum center wavelength tuning range of the SBGs is about 3.2nm. The measured laser spectrum at around 1533.53nm is shown in Fig. 5, wherein the –3dB linewidth is only ~40pm.

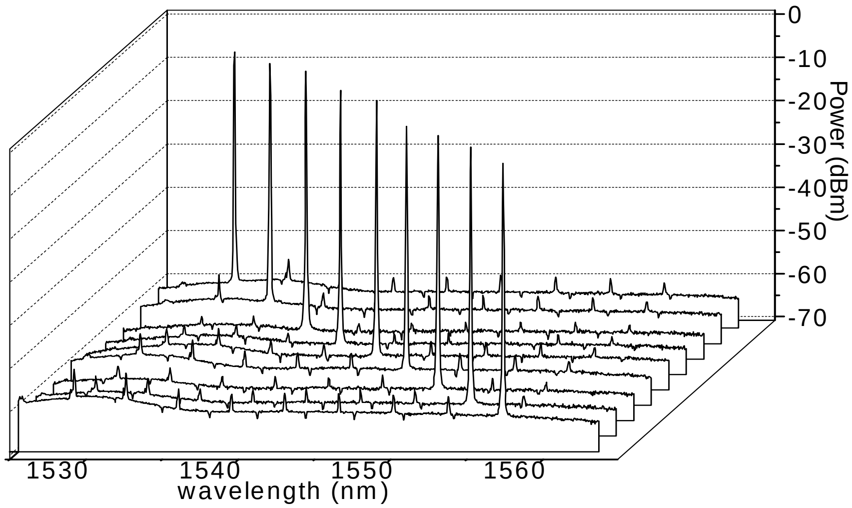


Fig. 4 Measured tuning characteristic of the fiber laser (one SBG fixed)

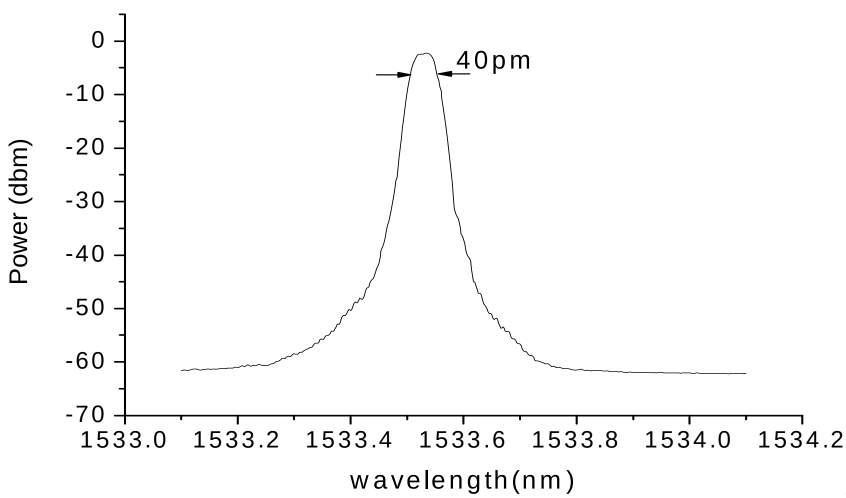


Fig. 5 Measured laser output spectrum at around 1533.53nm.

## 4. Conclusion

By changing the phase of each sample through on/off sampling modulation in a chirped SBG, SBGs with different channel spacing can be fabricated using only one chirped phase mask and a PZT-driven translation stage. The design principle and fabrication method of such SBGs are proposed, featuring in markedly improved fabrication easiness and nearly identical reflection response among all channels over a wide bandwidth. Using Erbium-doped fiber as gain medium and a pair of such SBGs (with different channel spacing to form vernier effect) as reflectors, a tunable DBR fiber laser with broadly tunable range (~30nm) and constant power output (difference less than 1 dB) has been demonstrated.

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