

The Design of a Low-Cost Tunable Laser Based on Reconstructed Equivalent Chirp

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Abstract: With the development of optical fiber communication, tunable laser design has become an international research hot spot. In this paper, a new type distributed feedback (DFB) tunable laser is introduced. It uses the Reconstruction-Equivalent-Chirp (REC) technology, combining the stepped chirp sampling structure and superstructure fiber Bragg grating structure. We can obtain continuous tunable multi-channel laser and achieve the purpose of eliminating chirp of the chirp pulse and compressing pulse width at the same time. Through the simulation calculation, it can be known that the output power of each laser's channel are roughly equal. The laser can realize the tuning between 1530 nm to 1560 nm. And for the initial pulse with the conditions of $T_{in} = 20$ ps, the chirp coefficient $C = 5$ and time-bandwidth product is 2.25, time-bandwidth product will change to 0.458 after REC compression. The compression ratio is about 5:1, which means the pulse frequency chirp can be basically eliminated. The structure only needs to be manufactured by traditional lithography. Its low cost and excellent performance leads to a good applied prospect.

1. The introduction

Optical fiber communication is one of the pillars of modern information transmission. Its transmission bandwidth, high anti-interference and small signal attenuation are much more better than the transmission of cable communication and microwave communication. It has become a major means of transmission in the communication all around the world. In optical fiber communication, laser is the core component and it has become a hot spot of domestic and foreign research. However, because of the constant improvement of the capacity of optical communications and transport requirements, the original single wavelength laser cannot meet the demand of modern optical communication capacity among society. Besides, the quantity of single lasers in complex optical communication network are huge, which means more difficult control, higher cost and more severe resource waste[1-3]. Therefore, how to manage the simultaneous transmission of multiple optical signals of different wavelengths and rates on a single optical fiber, in other words, the design of tunable lasers, has become a popular topic of scholars all over the world.

Tunable laser is a kind of laser which can change the continuous output wavelength. This kind of laser can have the emission of different wavelengths and greatly reduces the cost. So they could be widely used in sensing, bio-medicine, photonic integration, information processing and communication, etc. It has a huge promotion for practical applications. Many scholars have proposed different methods for tunable laser design. In monolithic integrated tunable laser, such as the tunable laser based on distributed amplification distributed feedback[4] structure or based on distributed Bragg reflection structure[5], mainly adjusting the emission wavelength of laser by temperature or current. It



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can achieve the wavelength adjusting by adding a laser cavity in waveguide grating filter. But the complex production of laser, huge time-consuming and high cost still needed to be handled. And there are still the deviation of wavelength. Then tunable laser based on multi-wavelength arrays appeared.[6] It tunes integrated DFB lasers' wavelength by temperature control and its tuning range is wide.[7] A TDA-DFB tunable laser structure of laser is proposed, which contains a tunable region and a gain region. This method consumes less energy by injecting current into the tuning region and controlling its refractive index and phase to change the corresponding Bragg wavelength.[8] Using a combination of integrated light source, waveguide grating multiplexers and optical amplifiers, a broadband spectral output can be divided into a group of optical frequency combs with precise intervals in frequency domain by the spectral segmentation method, thus becoming a stable array of output light sources.

However, the methods mentioned above all have a problem that when the demand of laser channels increases, the available low-cost lithography technology cannot meet the requirement of precision and the more precise techniques, such as electron beam etching, are too much more expensive. The consequence is that the lasers are expensive and the wavelength will deviate into the near spectral areas with the time or temperature change. It is hard to produce lasers with both high precision and low cost In practical application. Maintaining or improving the precision of laser while reducing the cost is the key problem to be solved urgently.

Therefore, this article introduces the design of Bragg grating based on restructure equivalent chirp (REC) technology and uses VPI optical simulation software to simulate real tunable laser which combines the technology of REC to get more simple laser structure and process. It has obtained good simulation results. The extensive tests on experimental platform show that the tunable laser has good characteristics of single mode and side-mode suppression ratio. You just need ordinary lithography to support the production, greatly reducing the cost of tunable laser and maintaining a high precision as well.

The first chapter is the introduction. It briefly introduces the development of optical communication and optical fiber communication and describes the crucial status of tunable laser in communication area. At the same time, it also introduces the research and principle of tunable laser, describing its wide applied prospect. The second chapter introduces the reconstruction equivalent chirp model, and proposes the optimization design of DFB laser by theoretical derivation and analysis. By designing and manufacturing special sampling structure, the equivalent phase shift is used to replace the real phase shift's function and effect so that the DFB laser meets the requirements of low performance and high cost. In the third chapter, based on the reconstruction equivalent chirp technology, the stepped chirp sampling grating structure is combined with the superstructure fiber grating structure to complete the design of continuous tunable laser. At the same time, the chirp is eliminated and the pulse width is compressed. In the fourth chapter, the simulation software is used to simulate the tunable laser with the stepped chirped sampling grating and the superstructure fiber Bragg grating. The result shows that the laser can eliminate chirp and get good multichannel reflection. The fifth chapter summarizes the results of each part and gives a further prospect of the existing problems.

2.Reconstruction-Equivalent-Chirp(REC) model

The Reconstruction-Equivalent-Chirp technology (REC technology), through special sampling of uniform grating, reduces the manufacturing process difficulty to the submicron level and obtains the equivalent effect with the nanoscale electron beam lithography, making the DFB laser meet the requirements of low cost and high performance. By designing and producing special sampling structure, equivalent phase shift in ± 1 level channel can be formed to replace the real phase shift's functions and performance in the multi-channel transmission spectrum formed by sampling grating.

Producing devices by REC technology needs to conduct special design sampling for uniform grating and then fabricate the designed special structure into devices.

The refractive index of the sampling grating can be expressed as:

$$\Delta n(z) = s(z) \exp\left(j \frac{2\pi z}{\Lambda}\right) + c.c \quad (1)$$

In this equation, Λ is grating period. $S(z)$ is a periodic function of the sampling period. $C.c$ is its complex conjugate. The conjugate part meets the equation $s(z)=1$ and the unconjugated part is 0.

Take the Fourier expansion of $s(z)$, and get:

$$s(z) = \sum_m F_m \exp\left(j \frac{2m\pi z}{P}\right) \quad (2)$$

In the equation, P is the sampling period and F_m is the Fourier coefficient corresponding to the m channel. Get:

$$\Delta n(z) = \frac{1}{2} \Delta n_s \sum_m F_m \exp\left[\left(j \frac{2\pi z}{1}\right) \bullet \left(\frac{m}{P} + \frac{1}{\Lambda}\right)\right] + c.c \quad (3)$$

The sampling grating is composed of many sub-gratings. So there are:

$$\frac{1}{\Lambda_m} = \left(\frac{m}{P} + \frac{1}{\Lambda}\right) \quad (4)$$

In the equation, Λ_m is the expression of m -level period. In level -1 channel, which means when $m=-1$, we usually take level -1 sub-grating. It is also known as target grating. We can obtain:

$$\frac{1}{\Lambda_{-1}} = \left(\frac{1}{\Lambda} - \frac{1}{P}\right) \quad (5)$$

Through the equation above, it can be known that when the period Λ of seed grating is constant, it is available to get any equivalent target grating period by changing the sampling grating period.

For the equation (4), if the sampling period of sampling grating at $z = z_0$ expand ΔP , sampling function will change to $s(z - \Delta P)$ when $z \geq z_0$. At this time, for the m -level channel, its refractive index modulation will change in $z \geq z_0$:

$$\Delta n_m(z) = \begin{cases} \frac{1}{2} \Delta n_s \sum_m F_m \exp\left[\left(j \frac{2\pi z}{1}\right) \bullet \left(\frac{m}{P} + \frac{1}{\Lambda}\right)\right], & z \leq z_0 \\ \frac{1}{2} \Delta n_s \sum_m F_m \exp\left[\left(j \frac{2\pi z}{1}\right) \bullet \left(\frac{mz}{P} + \frac{z}{\Lambda} - \frac{m\Delta P}{P}\right)\right], & z \geq z_0 \end{cases} \quad (6)$$

Thus, we get a phase-shift Φ_m in each channel:

$$\varphi_m = -2m\pi \frac{\Delta P}{P} \quad (7)$$

When ΔP changes continuously in a certain period of area, we can get the Equivalent Chirp. Considering the level -1 channel we usually use, when $\Delta P = P/2$, $\Phi_m = \pi$. So the equivalent grating π phase shift is be introduced at level -1 channel, which is the $\lambda/4$ phase shift.

Because the period of uniform grating Λ has been determined, Bragg wavelength λ_B has also been determined. The wavelength position of level -1 can be adjusted according to the difference of sampling period P .

$$\lambda_{-1} = \frac{2N_{eff} \bullet P \bullet \lambda_0}{2N_{eff} \bullet P - \lambda_0} \quad (8)$$

Among them, λ_0 and λ_{-1} respectively represent the wavelength of level 0 and level -1 channel. λ_0 is

denoted as the determined Bragg wavelength λ_B and N_{eff} is the effective refractive index.

So when the sampling period change suddenly at a certain position, the equivalent phase shift is introduced at this position. Therefore, the sampling period P required by the desired target wavelength can be obtained through theoretical calculation, which means reconstruct the grating structure. Because the sampling period is tens of order larger than the grating period of the basic grating, the influence of processing error on the wavelength in the manufacturing process can be more easily reduced. It is of great applied significance in the process of laser manufacturing.

3. The design of superstructure fiber grating based on stepped sampling

3.1. Stepped chirped sampling grating model

The typical distributed Bragg reflection (DBR) structure is usually used in the design of laser and its inner grating has a comb reflectance spectrum. In order to make the comb reflector's gain flat in the whole tuning range and get more uniform output power and higher side-mode suppression ratio (SMSR), we adopt the reconstruction equivalent chirp (REC) technique for the seed sampling of the uniform grating, creating efficient multichannel reflection in a wide wavelength range. The DBR laser has two multichannel SBGS with different channel intervals. Due to the vernier caliper effect, when only one SBG is tuned, only one pair of channels will overlap and the wavelength of this channel will be stimulated.

The grating is regarded as composed by several sections, each of which is a sampling period. The grating period in each sampling period remains unchanged and there is no chirp. The grating period is different among each sampling period, and it meets:

$$\Lambda_i(z) = \Lambda_0 - Cz, z_i < z < z_{i+1}, i = 1, 2, \dots, N, z \in \left[-\frac{L}{2}, \frac{L}{2}\right] \quad (9)$$

In the equation, $\Lambda_i(z)$ is the i -th grating period of sampling period, which means the Λ_s of the reconstruction equivalent chirp superstructure fiber grating; Λ_0 is the grating period of in the center location of the Bragg grating; C is the chirp coefficient of discontinuous linear chirp, indicating the change of grating period along the grating length; Z is the radial coordinate of the Bragg grating, and the origin of the coordinate is set at the center of the sampled Bragg grating; L is the total length of the grating; Z_i is the coordinates of the beginning of the i -th sampling period; Z_{i+1} represents the coordinates of the end of the i -th sampling period, that is, the $i+1$ -th sampling. In order to make the grating have vernier caliper effect, the chirp coefficient C and the sampling period P_L must meet:

$$\varphi + \frac{2\pi C}{\Lambda_0^2} P_L^2 = \frac{2\pi}{N} \quad (10)$$

We used the method of the reconstruction equivalent chirp to design the laser and substituted the sampling period formula of the stepped grating into it, obtaining the expression of the m -level channel grating refractive index which is corresponded to the sampled grating:

$$\Delta n_m(z) = \frac{1}{2} F_m A(z) \times \exp \left[j \frac{2m\pi f(z)}{P} + j\varphi(z) \right] \times \exp \left(j \frac{2\pi z}{\Lambda_i} + j \frac{2m\pi z}{P} \right) + c.c., \quad (11)$$

$$\Lambda_i(z) = \Lambda_0 - Cz, z_i < z < z_{i+1}, i = 1, 2, \dots, N, z \in \left[-\frac{L}{2}, \frac{L}{2}\right], \varphi_m + \frac{2\pi C}{\Lambda_0^2} P_L^2 = \frac{2\pi}{N}$$

P is the sampling period. F_m is the Fourier coefficient, corresponding to the m -level channel of the sampled grating. $\Phi_{\text{in}}(\omega)$ is the phase spectrum related to frequency.

3.2. The superstructure fiber grating design based on stepped sampling

The theory is reconstruction equivalent chirp superstructure fiber grating is modulating the sampling period of sampling grating (SBG), making a certain level reflection spectrum have a goal SBG

response. Just a phase mask template can produce all kinds of fiber grating with complex response function. Its significance lies in the change of the grating sampling period make the grating chirp effect possible, not only reduce the technological requirement but also bring about design flexibility.

According to 3.1, it can be known that:

$$\Lambda_i(z) = \Lambda_0 - Cz, z_i < z < z_{i+1}, i = 1, 2, \dots, N, z \in \left[-\frac{L}{2}, \frac{L}{2}\right] \quad (12)$$

Thus:

$$\frac{d\varphi(z)}{dz} = \omega = \frac{2\pi}{\Lambda_i(z)} = \frac{2\pi}{\Lambda_0 - Cz}, z_i < z < z_{i+1}, i = 1, 2, \dots, N, z \in \left[-\frac{L}{2}, \frac{L}{2}\right] \quad (13)$$

Then, the field intensity expression of any optical pulse can be written as:

$$E_c(t) = \sqrt{P_0} A(t) \exp(j\omega_0 t) \exp(j\varphi(t)) \quad (14)$$

In the formula, P_0 is the peak power of optical pulse, $A(t)$ is the envelope function of the pulse, ω_0 is the central carrier frequency of the pulse, and $\varphi(t)$ is the additional phase term which changes with time and its derivative with time is the frequency chirp.

The spectral information of $E_c(t)$ is

$$U_c(\omega) = \text{Fourier}[E_c(t)] = A_c(\omega) \exp(j\varphi_m(\omega)) \quad (15)$$

In this equation, $\varphi_m(\omega)$ is the Fourier transform of $\varphi(t)$.

After the chirp pulse enters a fiber grating, it will be reflected. The frequency domain expression of the optical field is

$$U_{out} = A_c(\omega) \exp(j\varphi_c) \exp(j\varphi_m(\omega)) \times \rho(\omega) \exp(j\varphi_1) \exp(j\varphi_s(\omega)) \quad (16)$$

In the equation, φ_1 is the constant term of the grating reflection spectrum phase which does not change with ω . $\varphi_s(\omega)$ is the spectral phase response related to ω . The transmitted time-domain waveform is:

$$E_{out}(t) = \text{Fourier}^{-1}[U_{out}(\omega)] = \frac{1}{2\pi} \int_{-\infty}^{\infty} A_c(\omega) \rho(\omega) \exp(j(\varphi_c + \varphi_1)) \times \exp(j(\varphi_m(\omega) + \varphi_s(\omega))) \exp(j\omega t) d\omega \quad (17)$$

In each individual grating period, the grating reflection spectrum meets

$$\frac{d\rho(\omega)}{d\omega} = 0, \varphi_s(\omega) = -\varphi_m(\omega) \quad (18)$$

In this equation:

$$\varphi_m(\omega) = \int_{-\infty}^{\infty} \frac{2\pi}{\Lambda_0 - Cz} dt, z_i < z < z_{i+1}, i = 1, 2, \dots, N, z \in \left[-\frac{L}{2}, \frac{L}{2}\right] \quad (19)$$

So the time domain signal becomes

$$E_{out}(t) = \frac{r}{2p} \int_{-\infty}^{\infty} A_c(\omega) \exp(j(j_c + j_1)) \exp(j\omega t) d\omega \quad (20)$$

It means that after the reflection of reflective spectrum fiber grating, the chirp pulse of any model, as shown in the above-mentioned conditions, will be compressed into the transform-limited pulse to achieve the purpose of eliminating the chirp and compressing the pulse width of the chirp pulse. That is the target response which can eliminate the chirp. The specific process of eliminating chirp by REC is shown in figure 1.

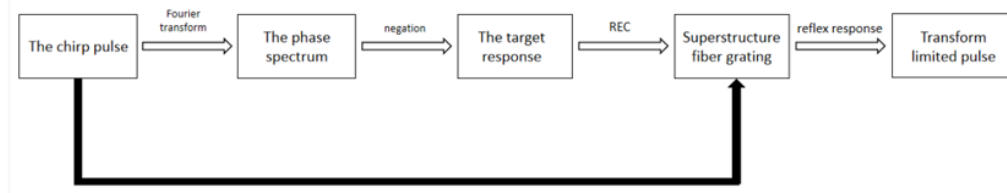


Figure 1. The specific process of eliminating chirp by REC

4. Simulation and analysis

In this paper, the wavelength intervals are 4.0 nm and 4.5 nm respectively. The length of phase shift area and the length of active area 100 μm and 400 μm respectively. Seed grating period is 263 nm and effective refractive index is 3.23. Δn_{eff} is 0.021. Other material parameters used in the simulation are listed in table 1.

Table 1. Grating structure parameters

Parameter	Unit	Number
Thickness of active waveguide part	$d/\mu\text{m}$	0.18
Thickness of passive waveguide part	$D_p/\mu\text{m}$	0.23
Width of waveguide	$W/\mu\text{m}$	2
Loss of waveguide	α_0/cm^{-1}	20
Effective reflectivity	N_{eff}	3.23
Transparent carrier concentration	$N_{\text{tr}}/\text{cm}^{-3}$	12×10^{18}
Carrier lifetime	T/s	4×10^{-9}

Figure 2 shows the comparison of reflection spectrum images between forward grating and backward grating. It can be seen from the figure that the two reflections spectrum overlap at 1533.06nm. So the emitted wavelength is 1533.06nm. Two grating with 0.5nm wavelength interval produce vernier caliper effect. The injection current of the forward grating remains unchanged while the injection current of the backward grating changes. Seven channels will be emitted and the output power is relatively consistent. The laser with a wavelength range of 30nm (from 1530nm to 1560nm) will be emitted, as shown in figure 3. If the current in the active region is changed, the output power of the light will increase accordingly. In other words, if the injection current of the two gratings is changed, the continuous light can be emitted from 1530nm to 1560nm, which can achieve efficient multi-channel reflection in a wider wavelength coverage range.

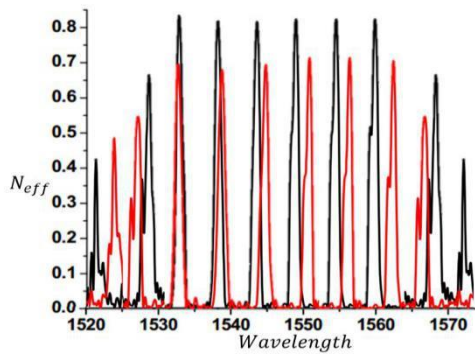


Figure 2. The spectrum of forward grating and backward grating

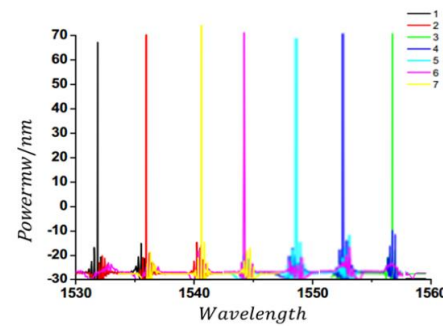


Figure 3. The simulative power of tunable laser

The parameters of the pulse in the linear chirp model are set as: the initial pulse width $T_{in}=20\text{ps}$, chirp coefficient $C=-5$ and time-bandwidth product is 2.25. The anti-chirp effect of the reconstructed reflection spectrum on the chirped pulse is shown in Figure 4. It can be seen from Figure 4 (a) that the pulse which has been eliminating chirp by REC has a very good coincidence degree with the pulse after eliminating chirp perfectly by the target response. The waveform is greatly compressed in the time domain. The pulse width $T_{out}=4\text{ps}$ and the compression ratio is close to 5:1. It can be seen from Figure 4 (b) that the frequency chirp of the pulse is basically completely eliminated and the residual chirp is close to zero, which is very close to the ideal situation. By calculation, the time-bandwidth product which is ideally compressed by target response is 0.443 and the time-bandwidth product which is compressed by REC is 0.458. They are very close to each other, indicating that the linear chirp has been perfectly eliminated. To sum up, the combination of this structure and the stepped grating can achieve excellent multi-channel reflection while eliminating the chirp.

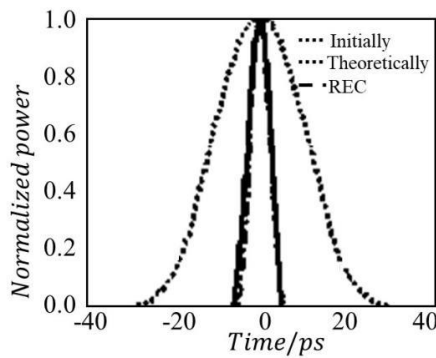


Figure 4(a). Waveform

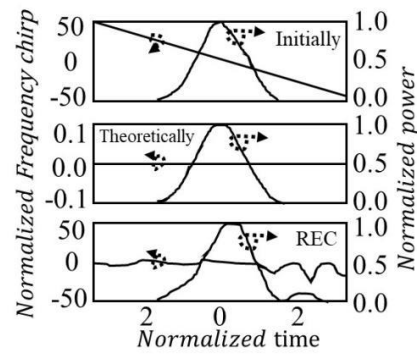


Figure 4(b). Chirp

5. Conclusion

In this paper, a new tunable laser design method is proposed, which combines the stepped chirp sampling structure with the superstructure fiber grating structure, and the theoretical feasibility and the condition of realization are deduced. This paper finishes the continuous tunable design of the laser, eliminates the chirp and compresses the pulse width. Because the laser can be produced by traditional lithography technology, it achieves the goal of combining low cost and high performance effectively, which is beneficial to mass production. However, the combination of the stepped sampling grating and superstructure fiber grating will make the grating structure more complex and propose higher requirements for the manufacturing process in the actual production process. Therefore, how to simplify the grating structure and improve the relevant manufacturing process still needs further research.

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