Beam Reflection by Transversely Chirped Volume Bragg Grating

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Abstract: Transversely chirped volume Bragg grating (TCVBG) provides tunability of resonant wavelength in different designs of laser cavities. Resonant reflectivity suppression and quality deterioration of Gaussian beam reflected by TCVBG are calculated, together with spectral characteristics.
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1. Introduction

Reflective uniform volume Bragg gratings (VBGs) in photo-thermo-refractive (PTR) glass are used as narrow-band output couplers in high-power lasers with different gain media [1]. VBGs with longitudinally chirped grating period are used for stretching and compression of ultrashort laser pulses in well established chirped pulse amplification schemes [2]. Here we discuss reflective VBGs with chirp of the resonant Bragg wavelength in transverse direction as it is presented in Figure 1a. Such VBGs have uniform refractive index modulation along the longitudinal direction of reflection at any particular transverse point of incidence. These transversely chirped volume Bragg gratings (TCVBGs) have been already implemented experimentally in different laser systems. One particular TCVBG has been used for locking and tuning of nanosecond optical parametric oscillator as shown in [3]. In another work, the wavelength tunability of narrow line fiber laser has been realized using similar TCVBG [4]. In both experimental realizations the results have demonstrated fulfillment of the designed goals.

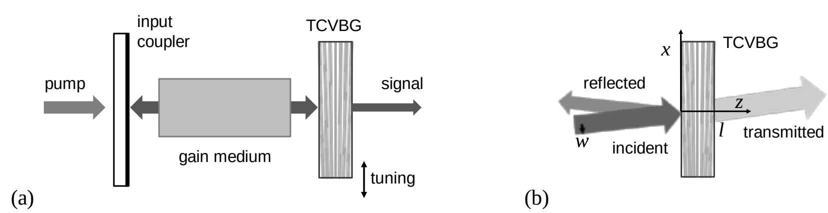


Fig. 1. (a) Laser cavity with TCVBG as output coupler; (b) Reflection of Gaussian beam from TCVBG.

In this work we provide detailed theoretical analysis of reflective properties of TCVBGs. While modeling of each particular type of laser cavity utilizing TCVBG requires numerical efforts involving many different parameters not directly related to parameters of TCVBG, e.g. size of pump beam, here we will concentrate on a study of TCVBG itself and will analyze its performance as narrow-band filter in terms of Gaussian beam reflection, see Figure 1b. For example, wide range of resonant wavelength tunability is preferred for many applications and it is directly related to large value of the transverse chirp rate. On the other hand, a Gaussian beam will experience significantly different amplitude reflection coefficients over its aperture in case of large chirp rate. That will lead to reflectivity reduction and beam quality deterioration. Our goal is to analyze the effect of transverse chirp rate $d\lambda_{res}/dx$ on reflection efficiency and reflected beam quality depending on Gaussian beam size w.

2. Reflection by longitudinally uniform Bragg grating

Let us consider a Gaussian beam of wavelength λ and size w incident on TCVBG of thickness $l = 2$ mm having resonant Bragg wavelength linearly dependent on transverse coordinate $\lambda_{res}(x) = \lambda_0 + d\lambda_{res}/dx \cdot x$, $\lambda_0 = 1.064$ μm, $k_0 = 2\pi n_0/\lambda_0$, $n_0 = 1.5$. Suppose, the modulation amplitude n_1 along z-axis of refractive index $n(x,z)$ provides reflectivity $R_0 = 0.99$ at exact Bragg resonance:

$$n(x,z) = n_0 + n_1 \cos(Q(x)z + \varphi(x)), \quad Q(x) = \frac{4\pi n_0}{\lambda_{res}(x)}, \quad \lambda_{res}(x) = \lambda_0 + \frac{d\lambda_{res}}{dx} x, \quad \varphi(x) = \varphi_0 + \nu x, \quad 0 \le z \le l. \tag{1}$$

For typical value $w = 0.5$ mm the corresponding diffraction distance $z_R = k_0 w^2/2 = 1.1$ m is much larger than l, so we can still use one-dimensional coupled wave theory for Bragg reflection problem at each transverse x-position of incidence. The amplitude reflection coefficient r for uniform Bragg grating is known in analytical form, see for example [5]:

$$r(\lambda,\gamma)=\frac{S\sinh G}{G\cosh G-i\Phi\sinh G},\quad G=\sqrt{S^2-\Phi^2},\quad S=\frac{\pi n_1}{\lambda_0}l,\quad \Phi=(k-\tfrac{1}{2}Q(x))l,\quad k=\frac{2\pi n_0}{\lambda}. \tag{2}$$

Here the parameter S, so called strength of reflection, defines resonant Bragg reflectivity $R_0=\tanh^2 S$, and Φ is dimensionless detuning. We did not include factor with linear phase $\varphi(x)$ into r because it will not affect total reflectivity and beam quality below. After introduction dimensionless transverse variable ξ the detuning equals

$$\Phi=Dl=\Phi_\lambda+\gamma\xi,\quad \xi=\frac{x}{w},\quad \Phi_\lambda=\frac{2\pi n_0 l(\lambda_0-\lambda)}{\lambda_0^2},\quad \gamma=\frac{2\pi n_0 l}{\lambda_0^2}\frac{d\lambda_{\mathrm{res}}}{dx}w. \tag{3}$$

It has wavelength dependent part Φ_λ at the center of incident beam and additional term $\gamma\xi$ due to transverse chirp.

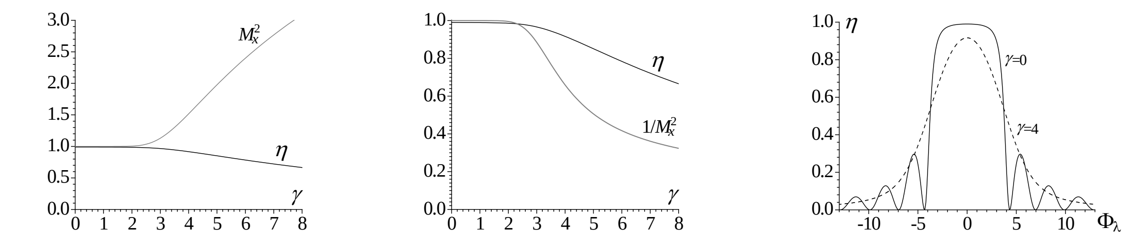
3. Reflectivity and quality of beam reflected by TCVBG

Total reflectivity η for incident Gaussian beam is defined by normalized integration of intensity $|b|^2$ of reflected beam along ξ. Deteriorated beam quality M_x^2 of reflected beam amplitude b can be calculated explicitly [6]:

$$\eta(\lambda,\gamma)=\int|b(\xi)|^2d\xi\Big/\int a^2(\xi)d\xi,\quad b=r(\lambda,\gamma)a,\quad a=e^{-\xi^2},\quad M_x^2=2\sqrt{[\langle x^2\rangle-\langle x\rangle^2][\langle u^2\rangle-\langle u\rangle^2]-[\langle xu\rangle-\langle x\rangle\langle u\rangle]^2},$$
$$\langle x^2\rangle=P^{-1}\int\xi^2|b|^2d\xi,\quad P=\int|b|^2d\xi,\quad \langle u^2\rangle=P^{-1}\int\left|\tfrac{db}{d\xi}\right|^2d\xi,\quad \langle xu\rangle=\tfrac{i}{2}P^{-1}\int\xi(\tfrac{db^*}{d\xi}b-b^*\tfrac{db}{d\xi})d\xi,\quad u=k\theta_x. \tag{4}$$

In integrals above, we omitted the same separable Gaussian y-dependence of incident and reflected beam profiles.

Figure 3a shows suppression of reflectivity η and deterioration of beam quality M_x^2 for incident Gaussian profile reflected by TCVBG. The dimensionless parameter γ introduced in Eq. (3) and proportional to transverse chirp is on horizontal axis. Figure 3b shows η and inverse value of M_x^2 for better understanding which effect is more prominent.



(a) (b) (c)

Fig.3.(a) Resonant reflectivity η and beam quality M_x^2 versus chirp rate γ; (b) η and $1/M_x^2$; (c) Reflection spectra of uniform VBG and of TCVBG.

We see that with large chirp rates the beam quality degradates faster than the reflectivity. For $\gamma=4$ we have $\eta=0.92$ and $M_x^2=1.52$; for parameters of incident beam and of Bragg grating mentioned before the corresponding chirp rate is equal $d\lambda_{\mathrm{res}}/dx=0.48$ nm/mm according to Eq. (3). Figure 3c demonstrates the washing out of spectral zeros with reflection from VBG with noticeable transverse chirp.

4. Conclusion

Reflective VBG with transverse chirp can be used for wavelength tuning in laser systems. With large chirp $d\lambda_{\mathrm{res}}/dx$, a degradation of the laser beam occurs. In order to prevent such degradation the chirp parameter γ from Eq. (3) should be kept minimal which can be achieved with reducing of beam size w and also of thickness l of VBG.

5. References

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