To narrow laser linewidth by utilizing dispersion characteristics of Gires-Tournois etalon

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A longer laser resonator length is benefit for laser linewidth, but harmful for single-frequency operation. A novel way is suggested to narrow the bandwidth of a Fabry-Perot (FP) cavity through increasing the derivative of one round-trip phase shift with respect to the frequency. It can be implemented by replacing one of two FP mirrors with a Gires-Tournois etalon (GTE), called FPGT, as a dispersion element. FPGT resonator has additional axial modes due to the GTE reflection phase shift. Theoretical analyses show that the bandwidth of additional axial modes can be 1% of that of a conventional FP cavity. A distributed feedback (DFB) laser diode can employ FPGT resonator to achieve ultra-narrow linewidth laser. It is shown that the effect of refractivity fluctuation in the gain medium on the linewidth is little, and kilohertz linewidth is achievable for such a device.

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Narrow linewidth laser is an essential requirement for a variety of applications, such as coherent optical communication, sensing[1], coherent ladar detection, and coherent optical frequency-domain reflectometry[2], which require highly coherent light sources with ~10 kHz linewidth. A laser diode is quite suitable for these applications as it is very compact and low-cost. However, typical linewidth reported for ordinary distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers is in megahertz level. The lowest linewidth reported for discrete mode laser diodes is about 100 kHz[3]. Now these applications have to employ solid or fiber lasers[4]. However, in order to operate in single frequency, filters are needed, which inevitably increases the loss that deteriorates laser performance.

Laser linewidth limit has been theoretically given by the Schawlow-Townes formula[5], $\Delta\omega_{\mathrm{OSC}} \approx \frac{N_2}{N_2-N_1} \times \frac{2h\omega}{P_{\mathrm{OSC}}} \times \Delta\omega_{\mathrm{C}}^2$, N_1 and N_2 are the mean population densities of laser lower and upper levels, respectively, h is the Planck's constant, ω is the angular frequency, P_{OSC} is the output power, and $\Delta\omega_{\mathrm{C}}$ is the "cold cavity" bandwidth of any axial modes in a laser resonator due to its external coupling, and is inversely proportional to the resonator length. When the optical path fluctuation in the resonator is taken into account, the practical laser linewidth limit is broadened[6]. Therefore, increasing the length of the resonator, reducing the optical path fluctuation and loss of the resonator are effective methods to narrow laser linewidth. Another way is to decrease the laser gain bandwidth, such as Brillouin fiber lasers[7] and injection locking.

In this letter, a novel composite resonator is suggested with the structure shown in Fig. 1. It consists of three mirrors (R, M1, and M2). M1 and M2 form a Gires-Tournois etalon (GTE), and R and GTE (as a reflector and dispersion element) compose a Fabry-Perot (FP) cavity. It is called as a FPGT resonator. The characteristics and bandwidth of FPGT resonator are theoretically analyzed and derived. Its application to a DFB diode laser and advantages are discussed in detail.

For a conventional FP cavity, its bandwidth $\Delta\nu$ is the frequency deviation from its axial mode frequency. The phase deviation caused by the frequency deviation is $\Delta\varphi = \frac{2(1-R)}{\sqrt{R}}$ (φ is one round-trip phase shift of the cavity), which is a constant depending on the external coupling factor R. Because $\Delta\nu \approx \frac{\partial\nu}{\partial\varphi}\Delta\varphi = \Delta\varphi/\frac{\partial\varphi}{\partial\nu}$, the bandwidth is inversely proportional to $\frac{\partial\varphi}{\partial\nu}$. Namely, the bandwidth can be narrowed by increasing $\frac{\partial\varphi}{\partial\nu}$. In this letter, GTE as a dispersion element is just used to increase $\frac{\partial\varphi}{\partial\nu}$.

A GTE is an asymmetric FP interferometer with a partially reflecting mirror M1 and a 100% back reflecting mirror M2. Hence, GTE has only reflection output. If neglecting the GTE's loss, the reflection power equals the incident power. So it acts as a dispersion element and its reflection phase shift is[8]

$$\Theta\left(R_{\mathrm{g}}, d\right) = 2\tan^{-1}\left[a\tan\left(\frac{2\pi d}{c}\nu\right)\right], \quad (1)$$

where $a = \frac{1+\sqrt{R_{\mathrm{g}}}}{1-\sqrt{R_{\mathrm{g}}}}$, R_{g} is the reflectivity of GTE front mirror M1, d is the GTE length, ν is the light frequency, and c is the light velocity in vacuum. When $d = 290\ \mu$m and R_{g}=0.96, the curve of the reflection phase shift versus wavelength is illustrated in Fig. 2(a) in which there is an abrupt phase change from $-\pi$ to $+\pi$ at 1.554966 μm.

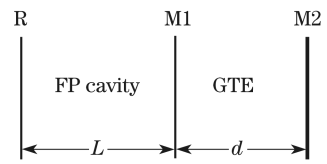

Fig. 1. Schematic of the FP cavity with a GTE.

Wavelengths associated with the abrupt phase change satisfy $2\pi d/\lambda = \pi m$ (m is a positive integer). Apparently, at these wavelengths, the derivative of the reflection phase shift with respect to frequency is very big.

GTE is used as one reflecting mirror of conventional FP cavity to compose the composite FP resonator in Fig. 1, called as FPGT resonator. The one round-trip phase shift of FPGT resonator is a sum of conventional FP cavity and the reflection phase shift $\Theta(R_g, d)$. The one round-trip phase shift of FPGT resonator is denoted as

$$\psi(\nu) = \frac{4\pi L}{c}\nu + 2\tan^{-1}\left[a\tan\left(\frac{2\pi d}{c}\nu\right)\right], \quad (2)$$

where $\frac{4\pi L}{c}\nu$ is the one round-trip phase shift of conventional FP cavity, and L is the length of the conventional FP cavity. As the practical GTE reflector is always lossy, the reflecting output of GTE is always less than 100%. So the effective reflectivity of GTE (its relative reflecting output) is denoted by R_e. For ease of comparison with the conventional FP cavity, R_e is assumed to be equal to R, the normalized intensity of FPGT resonator is

$$I(\lambda) = \frac{1}{1 + F \times \sin^2(\psi/2)}, \quad (3)$$

where $F = 4R_e/(1 - R_e)^2$. The axial mode of FPGT resonator is determined by $\psi(\nu) = m2\pi$ (m is a positive integer). Because $\Theta(R_g, d)$ has the abrupt change from $-\pi$ to $+\pi$ at the wavelengths satisfying $2\pi d/\lambda = \pi m$, FPGT resonator must have axial modes at these wavelengths. For comparison, the normalized intensity of FPGT resonator (R_e=0.98, R_g=0.96, d=290 μm, and L=300 μm) and the conventional FP cavity (R=0.98 and L=300 μm) are illustrated in Figs. 2(b) and (c), respectively. Figure 2(b) shows that there is an additional axial mode at the same wavelength as the abrupt phase change besides two axial modes of the conventional FP cavity, and the axial mode of the conventional FP cavity is shifted by a half axial interval due to the GTE π reflection phase shift. The bandwidth of additional axial mode is much narrower than the conventional one. The bandwidth of the additional mode can be derived by $\delta\nu \approx \delta\psi/\frac{\partial\psi}{\partial\nu}$, $\delta\psi = \frac{2(1-R_e)}{\sqrt{R_e}}$ is the phase deviation corresponding to half-maximum. In terms of Eq. (2), the derivative of $\psi(\nu)$ with respect to frequency is

$$\frac{d\psi}{d\nu} = \frac{4\pi L}{c} + 2\frac{a\sec^2\left(\frac{2\pi d}{c}\nu\right)}{1 + \left[a\tan\left(\frac{2\pi d}{c}\nu\right)\right]^2}\frac{2\pi d}{c}. \quad (4)$$

Because the frequency of additional modes satisfies $\frac{2\pi d}{c}\nu = \pi m$, $\frac{d\psi}{d\nu} = \frac{4\pi L}{c} + \frac{4\pi d}{c}a$. Hence, the bandwidth of additional modes is

$$\delta\nu \approx \delta\psi/\frac{d\psi}{d\nu} = \Delta\nu \times \frac{1 - \sqrt{R_g}}{(1 + d/L) - (1 - d/L)\sqrt{R_g}}, \quad (5)$$

where $\Delta\nu = \frac{c}{2L}/\frac{\pi\sqrt{R}}{1-R}$ is the bandwidth of the conventional FP cavity. Equation (5) shows that the bandwidth of additional modes $\delta\nu$ is $\frac{(1+d/L)-(1-d/L)\sqrt{R_g}}{1-\sqrt{R_g}}$ times less than that of the conventional FP cavity. In physics, resonating frequency is determined by the phase condition that ensures all circulating beams within its resonator in phase. As the phase deviation at half-maximum is a constant due to the resonator external coupling, the bigger $\frac{\partial\psi}{\partial\nu}$ is, the smaller the frequency deviation will be. In terms of above FPGT resonator parameters, $\frac{(1+d/L)-(1-d/L)\sqrt{R_g}}{1-\sqrt{R_g}} \approx 100$, therefore, the bandwidth of additional modes can be 1% of that of a conventional FP cavity. The amplified additional mode at 1.554966 μm is shown in Fig. 2(d).

The FPGT resonator can be used in a DFB laser diode to achieve ultra-narrow linewidth laser. The rear facet of the DFB laser serves as the partially reflecting mirror M1, and a mirror M2 is added, which can be implemented by micro-electro-mechanical system (MEMS) or other technologies. The GTE is formed by the rear facet and M2. We call this structured DFB laser as a DFBGT laser. The Bragg grating still works as a bandpass filter. When the center frequency of the grating is consistent with the additional mode due to GTE, the DFBGT laser will operate at the additional mode and in single frequency. Its center frequency and linewidth are mainly determined by the GTE spacing and the FPGT resonator, respectively. So its bandwidth still can be calculated by Eq. (5). If R = 0.96, R_g = 0.90, $d \approx$ 290 μm, $L \approx$ 300 μm, and assuming the GET's loss is 4%, $\delta\nu \approx \Delta\nu \times 0.025$. In terms of Schawlow-Townes formula, the linewidth of the DFBGT laser is nearly 1600 times narrower than that of a DFB laser. Therefore, the linewidth of DFBGT laser can be reduced from megahertz to kilohertz level by the application of FPGT resonator.

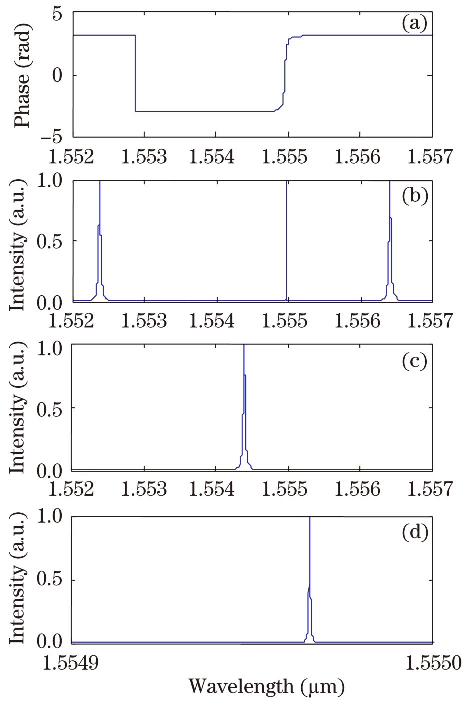

Fig. 2. (a) Reflection phase shift of GTE at d=290 μm and R_g=0.96; (b) normalized intensity of FPGT resonator at R=0.98, R_g=0.96, and L=300 μm, d=290 μm; (c) normalized intensity of conventional FP cavity at L=300 μm and R=0.98; (d) amplified additional mode of FPGT resonator at 1.554966 μm.

It is known that the performances of the DFB laser deteriorate when the reflecting light from the rear facet and the grating is not in phase[9]. For the DFBGT laser, because additional mode is the axial mode of FPGT resonator, the reflecting light from the GTE and the grating is always in phase. As the frequency of DFBGT laser is mainly determined by the GTE spacing, the refractivity fluctuation in the gain medium, which broadens the laser linewidth[10] by several times, has little effects on the DFBGT laser linewidth. Application of FPGT resonator can not only achieve ultra-narrow laser linewidth but also reduce the effect of refractivity fluctuation in active medium. The round-trip phase shift of the passive GTE is much more stable than that of the active cavity. The mode frequency can be better stabilized by stabilizing the GTE spacing. Then, GTE can also serve as a frequency stabilizer. However, the M1 reflectivity is related to the maximum single-frequency output power and the side mode suppression ratio. There is a trade-off between the linewidth and output power.

In conclusion, the dispersion characteristic of the GTE reflection phase shift is introduced into a FP cavity to narrow the laser linewidth. It gives a way that strong dispersion characteristics can be used to obtain ultra-narrow linewidth laser. It can narrow the laser linewidth by orders. When a DFB diode laser employs the FPGT resonator, with reasonable design of DFBGT laser parameters, kilohertz linewidth laser is achievable. The effects of the facet reflection and the optical path fluctuation of gain medium on its performances will almost be diminished in DFBGT laser.

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