Wavelength switching in multicavity lasers

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By controlling optical loss in a multiple cavity laser, it is possible to sequentially switch the lasing wavelength with a mode suppression ratio greater than ~35 dB. Our experiments use an antirefection coated semiconductor laser diode with optical feedback from Bragg gratings embedded in a single mode fiber. Residual reflectivity from the antirefection coating plays a critical role in determining device operation.

Recent advances in fiber Bragg grating (BG) technology present an opportunity to build novel hybrid optoelectronic devices. Previous work to control the lasing wavelength of semiconductor laser diodes using optical feedback from single mode fiber (SMF) BGs1–3 motivated us to study wavelength switching in such devices.

The inset to Fig. 1 shows our experimental arrangement. A 300-μm-long multiple quantum well semiconductor laser diode1 has a 0.1% antireflection (AR) coated facet on one side and a 32% reflecting mirror on the other. Optical emission at λ=1300 nm wavelength from the AR coated side of the semiconductor diode is coupled with 40% efficiency into a lensed SMF. The laser experiences optical feedback from two 1 mm long BGs embedded in the SMF with center wavelengths λ1=1311.7 and λ2=1310.4 nm and a ~3 dB optical bandwidth of 0.24 and 0.26 nm, respectively. Each BG has a 75% reflectivity and defines a distinct laser cavity with photon cavity round-trip time at a wavelength of λ1 (λ2) of 112 ps (138 ps).

When the lensed SMF is aligned to give the maximum coupling efficiency, laser threshold current is Ith=8 mA with emission at wavelength, λ1. Increasing the axial distance, z, between the AR coated facet of the semiconductor diode and the SMF decreases the optical coupling efficiency and increases the threshold current. Figure 1 shows light-current (L-I) characteristics for the indicated values of z. The L-I curves labeled 1, 3, and 5 lase at wavelength λ1 and the curves labeled 2 and 4 lase at wavelength λ2. Longitudinal modes of the external cavity are spaced 9 GHz (7.24 GHz) apart at λ1 (λ2). Because the BGs have a ~3 dB optical bandwidth of 42.72 GHz (46.28 GHz) at λ1 (λ2), a few longitudinal external cavity modes lie within the BG bandwidth at λ1 (λ2). The small discontinuities in the L-I characteristic seen in Fig. 1 likely occur due to mode hopping between longitudinal external cavity modes that lie within a given BGs optical bandwidth. Figure 2(a) shows the optical spectrum of light output as z increases for I=30 mA.

Residual reflectivity of the AR coated semiconductor facet gives rise to peaks in the optical spectrum away from the BG wavelength which correspond to Fabry–Perot (FP) modes of the semiconductor cavity. The FP mode spacing is ΔλFP=0.77 nm. Decreasing optical coupling efficiency between the semiconductor diode and the SMF causes an increase in threshold carrier density. This is due to an increase in optical gain needed to compensate for the increase in optical loss. An increase in carrier density in the semiconductor causes a decrease in the refractive index5 and moves the FP peaks of the semiconductor cavity to shorter wavelengths. Figure 2(a) shows that FP peaks in the spontaneous emission spectrum move to shorter wavelengths as z is increased.

The measured change in detected light intensity at wavelength λ1 (λ2) as z increased is illustrated in Fig. 2(b). This demonstrates that sequential wavelength switching of lasing light output at constant I is possible by changing the coupling efficiency between the semiconductor diode and the SMF.

Optical loss is minimized and lasing occurs at wavelength λ1 (λ2) when a FP peak in the spontaneous emission background of the semiconductor cavity coincides with the center wavelength of the BG at λ1 (λ2). In this manner, the small residual reflectivity of the AR coated facet can cause a large mode suppression ratio (MSR) when selecting lasing wavelengths. In our experiments, the MSR is in excess of ~35 dB.

A two-cavity model of the experimental arrangement shown in Fig. 3 is used to illustrate the role residual reflectivity from the AR coated facet plays in determining device operation.

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FIG. 1. Measured L-I characteristics as optical coupling efficiency between the semiconductor diode and the SMF is decreased by increasing z, the distance from the AR coated facet to the SMF. The inset shows a schematic of the experimental arrangement. Two BGs embedded in a SMF have center wavelengths of λ1=1311.7 nm and λ2=1310.4 nm and a ~3 dB optical bandwidth of 0.24 and 0.26 nm, respectively. The photon cavity round trip time at λ1 (λ2) is 112 ps (138 ps).
The section between mirrors with reflectivity \( r \) and \( r_1 \) corresponds to the laser gain medium and the section between \( r \) and \( r_2 \) corresponds to the portion of the laser cavity defined by SMF and BGs.

At the modes of the coupled cavity laser the denominator of Eq. (1) is real. For example, when \( \theta = 2n_0\pi + \pi \) and \( \phi = 2m_0\pi \) \((m_0 \) and \( n_0 \) are integers) the electric fields of the two cavities add and the gain, \( \alpha_0 \), to reach threshold is a minimum. To find the threshold gain under these conditions, the denominator, \( 1 - r_1r_Ge^{-j\phi} + r_2r_1G_0e^{-j(\theta + \phi)} \), is set to 0. At threshold, \( \alpha_0 = 4.62 \). For our 300-µm-long semiconductor region, this corresponds to a net gain (\( G_0 - \alpha_{\text{int}} \)) = 51 cm\(^{-1}\), where \( \Gamma \) is the optical confinement factor, \( g_0 \) is the optical gain of the mode, and \( \alpha_{\text{int}} \) is the internal loss. When, for example, \( \theta = 2n_1\pi \) and \( \phi = 2m_1\pi + \pi \) \((m_1 \) and \( n_1 \) are integers), the electric fields of the two cavities subtract and the required gain, \( G_1 \), to reach threshold is 5.48. This corresponds to a net gain (\( G_1 - \alpha_{\text{int}} \)) = 56.7 cm\(^{-1}\).

Rate equation analysis\(^7\) is used to calculate the laser MSR. Net gain at the threshold for the two modes under consideration is assumed to be as calculated above. The analysis is similar to the approach followed in Ref. 8. The spontaneous emission factor is \( \beta = 10^{-3} \) and other parameters for the device are taken from Ref. 7. For a lasing light output power of 1 mW from the 32% reflecting mirror \( r_1 \) and for the other nonlasing mode \( \alpha_m + (\alpha_{\text{int}} - \Gamma g_0) = 0.001 \) cm\(^{-1}\) and for the other nonlasing mode \( \alpha_m + (\alpha_{\text{int}} - \Gamma g_1) = 5.7 \) cm\(^{-1}\). The MSR at a light output power of 1 mW is \(-10\log[\alpha_m + (\alpha_{\text{int}} - \Gamma g_1)][\alpha_m + (\alpha_{\text{int}} - \Gamma g_0)]\) = -36 dB. MSR has a maximum when \( r = r_2/2 \) giving MSR = -44 dB for a light output power of 1 mW.

In our experiments, carrier density in the laser gain medium is changed by mechanically moving the lensed SMF thereby controlling optical loss. Clearly, mechanical movement limits wavelength switching speed. High-speed (Gb/s) wavelength switching may be possible by using electronic or optical injection to achieve carrier density changes in the semiconductor gain medium.

In conclusion, we have demonstrated that coupled cavity effects may be used to sequentially switch lasing wavelength at a constant injection current. The device makes use of a semiconductor laser diode in an external cavity with optical feedback from discrete BGs embedded in a SMF. Residual reflectivity from the AR-coated facet of the diode gives rise to the large MSR achieved in our experiments.

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