# 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 antireflection coated semiconductor laser diode with optical feedback from Bragg gratings embedded in a single mode fiber. Residual reflectivity from the antireflection coating plays a critical role in determining device operation. © *1997 American Institute of Physics.*
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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 didoes using optical feedback from single mode fiber (SMF) BGs[1–3] motivated us to study wavelength switching in such devices.

The inset to Fig. 1 shows our experimental arrangement. A 300-$\mu$m-long multiple quantum well semiconductor laser diode[4] has a 0.1% antireflection (AR) coated facet on one side and a 32% reflecting mirror on the other. Optical emission at $\lambda = 1300$ 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 $\lambda_1 = 1311.7$ and $\lambda_2 = 1310.4$ 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 $\lambda_1$ $(\lambda_2)$ of 112 ps (138 ps).

When the lensed SMF is aligned to give the maximum coupling efficiency, laser threshold current is $I_{\mathrm{th}} = 8$ mA with emission at wavelength, $\lambda_1$. 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 $\lambda_1$ and the curves labeled 2 and 4 lase at wavelength $\lambda_2$. Longitudinal modes of the external cavity are spaced 9 GHz (7.24 GHz) apart at $\lambda_1$ $(\lambda_2)$. Because the BGs have a −3 dB optical bandwidth of 42.72 GHz (46.28 GHz) at $\lambda_1$ $(\lambda_2)$, a few longitudinal external cavity modes lie within the BG bandwidth at $\lambda_1$ $(\lambda_2)$. 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 $\Delta\lambda_{\mathrm{FP}} = 0.77$ 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 index[5] 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 $\lambda_1$ $(\lambda_2)$ as $z$ is 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 $\lambda_1$ $(\lambda_2)$ when a FP peak in the spontaneous emission background of the semiconductor cavity coincides with the center wavelength of the BG at $\lambda_1$ $(\lambda_2)$. 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

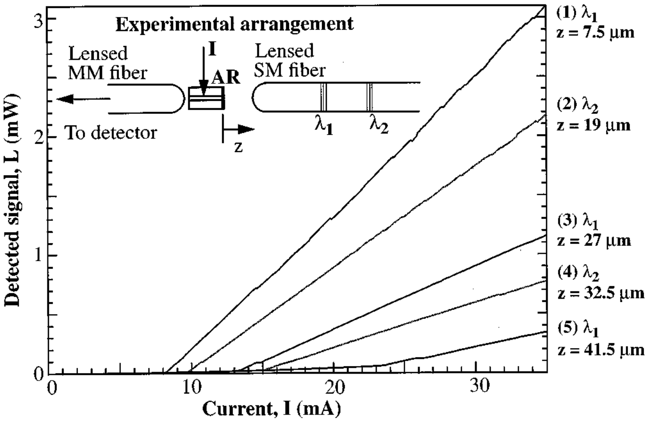

FIG. 1. Measured L-I characteristics as optical coupling efficiency between the semiconductor diode and the SMF is decreased by increasing $z$, the distance from the AR coated facet to the SMF. The inset shows a schematic of the experimental arrangement. Two BGs embedded in a SMF have center wavelengths of $\lambda_1 = 1311.7$ nm and $\lambda_2 = 1310.4$ nm and a −3 dB optical bandwidth of 0.24 and 0.26 nm, respectively. The photon cavity round trip time at $\lambda_1$ $(\lambda_2)$ is 112 ps (138 ps).

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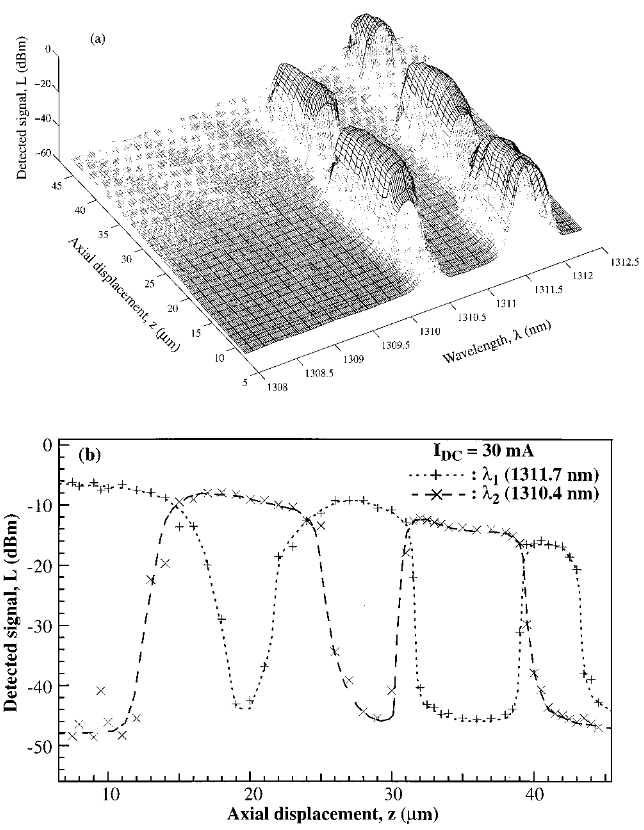

FIG. 2. (a) Measured optical spectrum for $I=30$ mA as the axial distance from the lensed SMF to the AR coated facet, $z$, is increased. With increasing $z$, peaks in the spontaneous emission background move to shorter wavelength. (b) Measured light intensity at $\lambda_1$ ($\lambda_2$) as $z$ increases illustrating sequential wavelength switching.

operation. The electric-field reflection coefficient $r_1=0.57$ corresponds to an intensity reflectivity of 32% for the cleaved facet of the semiconductor diode. The residual electric-field reflectivity of the AR coated facet is $r=0.03$. The electric-field reflectivity $r_2=0.35$ corresponds to an estimated 12% light coupled back into the laser due to optical feedback at the center wavelength of the BG. The cavity between $r_1$ and $r$ represents the semiconductor gain medium with a roundtrip gain, $G$, and an accumulated phase, $e^{-j\phi}$. The section between $r$ and $r_2$ represents the BG-defined external cavity having a round trip accumulated phase change of $e^{-j\theta}$ for the electric field.

The effective reflectivity of the coupled cavity system is[6]

$$r_{\text{eff}}=\frac{E_{\text{ref}}}{E_{\text{inc}}}=\frac{r(1-r_2re^{-j\theta})-Ge^{-j\phi}(r-r_2e^{-j\theta})}{1-r_2re^{-j\theta}-r_1rGe^{-j\phi}+r_1r_2Ge^{-j(\theta+\phi)}},\tag{1}$$

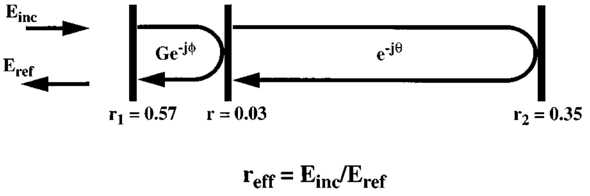

FIG. 3. Schematic diagram of a coupled cavity laser used for calculations. The section between mirrors with reflectivity $r$ and $r_1$ corresponds to the laser gain medium and the section between $r$ and $r_2$ corresponds to the portion of the laser cavity defined by SMF and BGs.

where $E_{\text{inc}}$ is the incident electric field and $E_{\text{ref}}$ is the reflected electric field. The effective reflectivity $r_{\text{eff}}$ is defined as $E_{\text{ref}}/E_{\text{inc}}$. At the lasing threshold, the denominator in the above equation approaches zero. Near and above threshold the term $rr_2e^{-j\theta}$ may be neglected in comparison to the other two terms in the denominator which are multiplied by the round trip gain $G$ of the semiconductor diode. $r_1rGe^{-j\phi}$ corresponds to modes of the semiconductor diode due to the residual reflectivity of the AR coated facet and $r_2r_1Ge^{-j(\theta+\phi)}$ corresponds to modes of the external BG-defined cavity.

At the modes of the coupled cavity laser the denominator of Eq. (1) is real. For example, when $\theta=2n_0\pi+\pi$ and $\phi=2\ m_0\pi$ ($m_0$ and $n_0$ are integers) the electric fields of the two cavities add and the gain, $G_0$, to reach threshold is a minimum. To find the threshold gain under these conditions, the denominator, $1-r_1rG_0e^{-j\phi}+r_2r_1G_0e^{-j(\theta+\phi)}$, is set to 0. At threshold, $G_0=4.62$. For our 300-$\mu$m-long semiconductor region, this corresponds to a net gain ($\Gamma g_0-\alpha_{\text{int}})=51\ \text{cm}^{-1}$, 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 $(\Gamma g_1-\alpha_{\text{int}})=56.7\ \text{cm}^{-1}$.

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 $\beta=10^{-5}$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 $\alpha_m+(\alpha_{\text{int}}-\Gamma g_0)=0.001\,36\ \text{cm}^{-1}$ and for the other nonlasing mode $\alpha_m+(\alpha_{\text{int}}-\Gamma g_1)=5.7\ \text{cm}^{-1}$. 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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