

A multistate external cavity laser diode

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A semiconductor laser diode in a photon cavity containing a mirror whose optical bandwidth is less than the classical cavity mode spacing can have multiple lasing states at the same bias current. The physics determining the behavior of this nonlinear multistate device is self-consistency between photon number, carrier number, and refractive index. © 1998 American Institute of Physics. [S0003-6951(98)03518-9]

Fiber Bragg gratings (BGs) may be used to provide wavelength selective feedback to antireflection (AR) coated semiconductor lasers in external cavity configurations.^{1,2} We show that multiple lasing states at the same bias current exist if the optical bandwidth of the BG is less than the classical mode spacing ($\Delta\lambda_C$) of the external cavity laser.

A schematic diagram of the physical arrangement and mathematical model used for simulation is illustrated in Figs. 1(a) and 1(b). Electric-field amplitude incident on a mirror at optical wavelength λ is $a_m(\lambda)$, while electric-field amplitude moving away from the mirror is $b_m(\lambda)$. The field amplitudes are normalized such that $|a_n|^2$ ($|b_n|^2$) gives the intensity or power flow in the medium. Electric-field reflectivity of the cleaved facet of the laser is $r_1=0.57$. Electric-field reflectivity of the AR coating is r , while transmission coefficient is jt such that $|r|^2 + |t|^2 = 1$, where $j = (-1)^{1/2}$.

The BG with center wavelength λ_0 at a distance L_0 from the AR coated facet of the laser has a reflection coefficient

$$r_2(\lambda) = r_{20} \exp\{[2(\lambda - \lambda_0)/(\Delta\lambda_{BG})]^2\}, \quad (1)$$

where $\lambda_0 = 1.52 \times 10^{-4}$ cm is the center wavelength of the BG. In our model $r_{20} = |C_C|^2 r_0 = 0.37$, where $r_0 = 0.95$ is the peak electric-field reflection coefficient at λ_0 and $C_C = 0.63$ is the coupling coefficient of the electric field between the AR coated facet of the semiconductor laser and the lensed single-mode fiber (SMF). For the static characteristics of the laser, the phase response of the BG as well as the phase of the electric-field coupling coefficient C_C is ignored.

In the resonance amplifier model³ the distributed spontaneous emission is replaced by two electric field inputs at the mirrors of the laser gain medium. The equivalent input is given by

$$wd \frac{|u_1|^2}{h\nu} \frac{c}{n_s} = \frac{1}{2} \beta B n^2 wd L_s, \quad (2)$$

where $w = 2 \mu\text{m}$, $d = 0.2 \mu\text{m}$, and $L_s = 300 \mu\text{m}$ are the width, depth, and length of the laser active region, respectively, h is Planck's constant, Bn is the spontaneous recombination rate at carrier density n , $\beta = 10^{-6}$ is the spontaneous emission factor, c is the speed of light in free space, ν is the frequency of the electric field ($\nu = c/\lambda$), and n_s is the refractive index of the laser gain medium whose variation as a function of

carrier density is $n_s = n_{s0} - D_{ns}(n - n_c)$, where $n_{s0} = 3.75$ is the refractive index of the gain medium at a carrier density of $n_c = 2.2 \times 10^{18} \text{ cm}^{-3}$ and $D_{ns} = 7 \times 10^{-21} \text{ cm}^3$ is the change of refractive index with carrier density. The spontaneous emission electric field amplitude u_1 at λ is normalized such that $|u_1|^2$ gives the energy density stored in the electric field.

Using methods outlined in Ref. 4 one obtains

$$a_1(\lambda) \cong \frac{u_1(\lambda)}{[1 - p_1(\lambda)^2 r r_1 - p_2(\lambda)^2 r r_2 + p_2(\lambda)^2 p_1(\lambda)^2 r_1 r_2]}, \quad (3)$$

where $p_1(\lambda)$ and $p_2(\lambda)$ is the electric field propagation in the semiconductor cavity and the BG defined external cavities respectively. $p_2(\lambda) = \exp(-j\theta/2)$, where $\theta = 4\pi n_g L_0/\lambda$, and $n_g = 1.5$ is the effective refractive index of the SMF at the wavelength of interest and $L_0 = 0.5$ cm is the length of the external cavity. $p_1(\lambda) = G^{1/2} \exp(-j\phi/2)$,

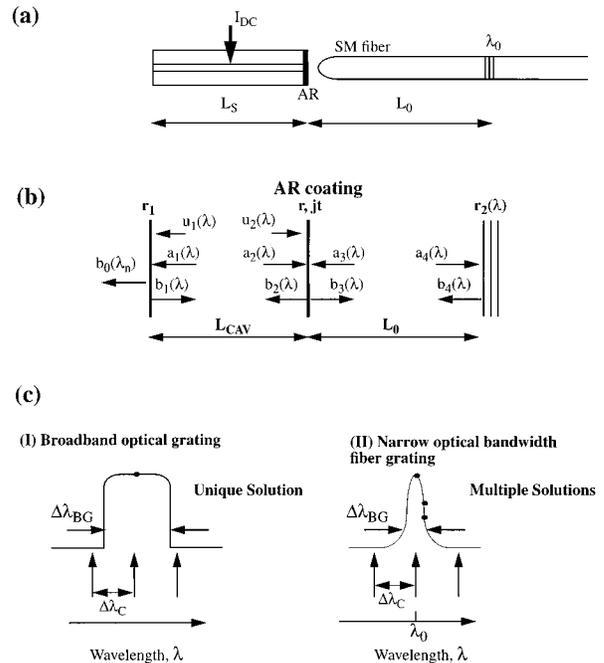


FIG. 1. (a) Schematic diagram of the experimental arrangement and (b) illustration of the external cavity laser model used for simulation. (c) Schematic illustrating (I) unique solution for $\Delta\lambda_{BG} > \Delta\lambda_C$ and (II) multiple solutions obtained for narrow optical bandwidth fiber grating when $\Delta\lambda_{BG} < \Delta\lambda_C$.

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where $\phi = 4\pi m_s(n)L_s/\lambda$, and G is the electric-field gain for one photon cavity round trip. The cavity round-trip electric-field gain $G = \exp[(\Gamma a \log(n/n_0) - \alpha_i)L_{\text{CAV}}]$, where $n_0 = 1 \times 10^{18} \text{ cm}^{-3}$ is the transparency carrier density, $\alpha_i = 35 \text{ cm}^{-1}$ is the internal loss coefficient, $a = 361 \text{ cm}^{-1}$ is the gain constant, and $\Gamma = 0.25$ is the optical confinement factor.

The total number of photons in the semiconductor cavity is $S = E/h\nu$, where E is the energy stored in the electric field obtained by integrating the electric-field intensity over the semiconductor cavity,

$$E \cong wd \left(\frac{1 - |p_1(\lambda)|}{\Gamma a \log((n/n_0) - \alpha_i)} \right) [2|a_1(\lambda)|^2]. \quad (4)$$

Steady-state n is given by the setting $dn/dt = 0$ in the conventional semiconductor laser rate equation.⁵ The carrier lifetime is modeled as $\tau_n = 1/(A + Bn + Cn^2)$, where $A = 10^6 \text{ s}^{-1}$, $B = 10^8 \text{ cm}^3 \text{ s}^{-1}$, and $C = 0.6 \times 10^{-26} \text{ cm}^6 \text{ s}^{-1}$. To find self-consistent solutions one uses the conventional carrier density rate equation, Eq. (4), and finds λ requiring that the denominator of Eq. (3) be purely real. Simulations indicate that when $\Delta\lambda_{\text{BG}} > \Delta\lambda_c$ the laser has a unique solution at all drive currents. However, when $\Delta\lambda_{\text{BG}} < \Delta\lambda_c$ multiple lasing solutions exist.

To better understand why the narrow grating bandwidth results in multiple lasing states, consider a perfectly AR coated semiconductor laser ($r = 0$) in an external cavity with optical feedback from a BG. The electric field of the lasing mode can be written as

$$a_1(\lambda) \cong \frac{u_1(\lambda)}{1 + G(n)r_1r_2(\lambda)\exp\{-j[\theta(\lambda) + \phi(\lambda)]\}}. \quad (5)$$

For a physical steady-state solution, the denominator of Eq. (5) should be purely real. Hence

$$\theta(\lambda) + \phi(\lambda) = (2m + 1)\pi, \quad (6)$$

where m is a positive integer. Equation (6) can be solved for the lasing wavelength λ of the light output for a given carrier density, n . For any n , there exists a wavelength λ within the cavity mode spacing, $\Delta\lambda_c = \lambda_0^2/[2(n_gL_0 + n_sL_s)]$, that satisfies Eq. (6). When lasing at wavelength λ the denominator of Eq. (5) may be simplified as

$$[1 + G(n)r_1r_2(\lambda)] \rightarrow 0. \quad (7)$$

For a steady-state solution, the number of lasing photons obtained by substituting $a_1(\lambda)$ into Eq. (4) should give a self-consistent solution for n obtained using the conventional rate equation.

Consider the flat-top fiber BG illustrated in Fig. 1(c). If $\Delta\lambda_{\text{BG}} > \Delta\lambda_c$, then for any n there is a wavelength, λ_1 , within $\Delta\lambda_{\text{BG}}$ which satisfies Eq. (6). Hence, $r_2(\lambda) = r_{20}$ at the lasing wavelength. In this case Eq. (7) can be simplified as $1 - G(n)r_1r_{20} \rightarrow 0$. Since $G(n)$ increases monotonically with carrier density an unique value $n = n_1$ will satisfy the system of equations above laser threshold. For $n < n_1$, no mode will lase and for $n > n_1$, a mode within the grating bandwidth will have net round-trip gain greater than 1 which is not a physical solution.

When the grating bandwidth is narrow compared to the cavity mode spacing multiple solutions are possible. The la-

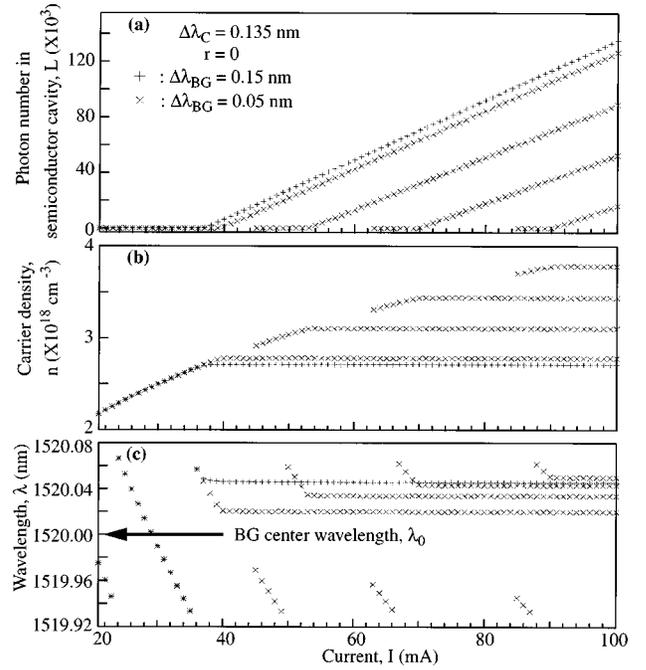


FIG. 2. Results of simulation showing existence of multiple steady-state lasing states at a given current bias when $\Delta\lambda_{\text{BG}} < \Delta\lambda_c$. (a) Total number of photons in the semiconductor gain medium as a function of current. (b) Carrier density in the laser gain medium as a function of bias current. As the bias current increases, lasing can occur at new states that require higher carrier density in the gain medium. (c) Wavelength of light output from the device with bias current. Lasing states exist on the short wavelength side of λ_0 .

ser can lase at λ_1 and n_1 when $1 - G(n_1)r_1r_2(\lambda_1) \rightarrow 0$ and lase at λ_2 and n_2 ($n_2 > n_1$), when $1 - G(n_2)r_2r_2(\lambda_2) \rightarrow 0$. The increase in round-trip gain $G(n)$ at the carrier density n_2 compared to n_1 is compensated for by a decrease in the mirror reflectivity, $r_2(\lambda_2)$.

Figure 2 shows the static characteristic of the laser diode in an external cavity with optical feedback from a single BG embedded in a SMF. The simulation assumes an ideal AR coating ($r = 0$) and $\Delta\lambda_c = 0.135 \text{ nm}$. It is interesting to note that lasing output is on the long wavelength side of λ_0 . As D_{ns} is negative with increase in bias current the carrier density in the laser gain medium increases causing the wavelength of the light output to tune to shorter wavelength. Because the increase in carrier density tunes the lasing mode closer to λ_0 , the device is stable. However, states on the shorter side of λ_0 are unstable.

It is worth mentioning that wavelength bistability has been predicted⁶ and observed⁷ in coupled-cavity semiconductor lasers. The bistability in these lasers is due to coupling between modes of two cavities of the laser. A similar bistability is seen in the device discussed in this paper when the AR coated facet of the laser is assumed to have a finite residual facet reflectivity and $\Delta\lambda_{\text{BG}} > \Delta\lambda_c$. The multiple solutions predicted in this paper when $\Delta\lambda_{\text{BG}} < \Delta\lambda_c$ is not due to coupled-cavity effects. There are multiple lasing states at the same bias current even when the residual facet reflectivity of the AR coating is reduced to zero. Our result shows that a laser in an external photon cavity with a mirror whose optical bandwidth is less than the classical cavity mode spacing can have multiple lasing states at the same bias current.

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