Beam shaping in spatially modulated broad-area semiconductor amplifiers

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We propose and analyze a beam-shaping mechanism that in broad-area semiconductor amplifiers occurs due to spatial pump modulation on a micrometer scale. The study, performed under realistic parameters and conditions, predicts a spatial (angular) filtering of the radiation, which leads to a substantial improvement of the spatial quality of the beam during amplification. Quantitative analysis of spatial filtering performance is presented based on numerical integration of the paraxial propagation model and on analytical estimations.

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Broad-area semiconductor (BAS) lasers (also called edge-emitting lasers) are technologically relevant light sources. The main advantage of such lasers is their high conversion efficiency, as the planar configuration enables efficient access of the pump to the whole volume of the active amplifying medium. BAS lasers, however, have a serious disadvantage as the spatial and temporal quality of the emitted beam is relatively low [1]. If no special mechanisms are incorporated in the design, such as different schemes of optical injection [2,3] or optical feedback [4,5], among others, the emission exhibits spatiotemporal fluctuations and is of a broad and noisy optical and angular spectrum. The poor spatial quality of the emitted beam is principally due to the absence of a natural angular selection mechanism in the large-aspect-ratio cavity of such devices. In addition, the Bespalov and Talanov [6] modulation instability in strongly nonlinear regimes leads to filamentation and deteriorates the quality of the emission.

In the absence of cavity mirrors, such planar semiconductor structures can act as light amplifiers. In the present work, we study the influence of periodic microstructuring of BAS amplifiers on the spatial quality of the amplified beam. We consider a two-dimensional modulation of the gain function, which can be achieved using a periodic grid of electrodes for electrically pumped semiconductors, as illustrated in Fig. 1. The main result presented in this Letter is that the spatial quality of the amplified beam can be substantially improved by periodic modulation of the spatial pump profile on a scale of several wavelengths.

Previous studies show that a periodic gain/loss (GL) modulation on the wavelength scale can lead to particular beam propagation effects, such as self-collimation, spatial (angular) filtering, or beam focalization [7,8]. In semiconductor media, due to the linewidth enhancement factor (Henry factor) α_H a periodic spatial pump distribution causes a combined gain and refraction index modulation (GIM). We note that a specific and different GIM case is being intensively studied in systems with broken parity-time symmetry [9,10]. Here we show that the angular spectrum of the radiation through a GIM amplifier becomes narrower while being amplified. For sufficiently long propagation distances (of the order of millimeters), the normalized beam quality factor M^2 [11] can reduce down to unity, indicating that the BAS amplifier output becomes perfectly Gaussian even for strongly random input beam profiles.

A typical BAS amplifier is 1–3 mm long and 0.3–0.5 mm wide, and the electromagnetic field is well confined in the vertical waveguiding plane. The gain coefficient in inverted (pumped) semiconductor media can reach values of $10^4\ \mathrm{m}^{-1}$ [12]. Note that patterning the semiconductor through a fishnet electrode, as here considered, is technologically feasible. Moreover, other approaches providing periodic gain, such as periodic microstructuring of the amplifying media, are possible. Given that the exact form of the pump modulation function is not critical, we assume that the pump profile is harmonically modulated. Furthermore, carrier diffusion usually smoothens spatial distributions, making them harmonic despite the steplike pump profile of electrodes.

In this Letter we consider a simplified model,

$$\frac{\partial A}{\partial z} = \frac{i}{2}\frac{\partial^2 A}{\partial x^2} + \left[\frac{p(x,z)-1}{1+|A|^2}(1-i\alpha_H) - i\alpha_H - \gamma\right]A, \quad (1)$$

which governs the evolution of the optical beam injected at $z = 0$. The complex amplitude of the electric field,

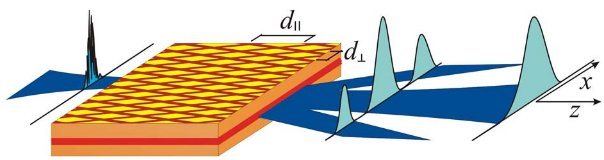

Fig. 1. (Color online) Planar semiconductor amplifier structure with fishnet electrodes. The pump profile is periodically modulated in space with transverse and longitudinal periods $d_\perp$ and $d_\parallel$. The incident beam of low spatial quality is amplified while its spatial structure is progressively improved. A part of the radiation is, however, lost in sideband components.

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$A(x,z)$, evolves in paraxial approximation experiencing diffraction, nonlinearities (due to the gain and refractive index dependence on the carrier density), and linear losses, γ. The spatial coordinates are normalized to reduced wavelength $\bar{\lambda} = \lambda/2\pi$, where λ is the central wavelength of the injected beam inside the semiconductor. Equation (1) is derived from the traveling-wave model [13–15] neglecting gain dispersion, assuming only linear spontaneous recombination, and adiabatically eliminating the carrier density.

An important ingredient in Eq. (1) is the spatially modulated gain $p(x,z) = p_0 + 4m \cdot \cos(q_\perp x)\cos(q_\parallel z)$, which is proportional to the pump profile smoothed by carrier diffusion with a factor $(1 + D(q_\perp^2 + q_\parallel^2))^{-1}$. The geometry is defined by the normalized longitudinal, $q_\parallel = \lambda/d_\parallel$, and transverse, $q_\perp = \lambda/d_\perp$, components of the lattice wave-vectors. They define the adimensional geometry factor $Q = 2q_\parallel/q_\perp^2 = 2d_\perp^2/\lambda d_\parallel$.

We study the amplification within the linear regime of Eq. (1), which is suitable for relatively weak fields with no sensible gain depletion.

For analytical estimations we apply a harmonic expansion of field in terms of the periodicities of the pump modulation,

$$A(x,z) = e^{ik_\perp x}\lfloor a_0(z) + a_{-1}(z)e^{-iq_\perp x - iq_\parallel z} + a_1(z)e^{+iq_\perp x - iq_\parallel z} + \cdots\rfloor \quad (2)$$

which, inserted into Eq. (1), gives

$$da_0/dz = \left(\frac{-i}{2}k_\perp^2 + g\right)a_0 + (1 - i\alpha_H)m(a_1 + a_{-1}), \quad (3a)$$

$$da_{\pm 1}/dz = \left(\frac{-i}{2}(k_\perp \pm q_\perp)^2 + iq_\parallel + g\right)a_{\pm 1} + (1 - i\alpha_H)ma_0. \quad (3b)$$

Note that the constant part of the complex gain $g = p_0(1 - i\alpha_H) - 1 - \gamma$ implies an exponential growth/decay of the total field and can be neglected when studying the spatial effects of a propagating beam.

We perform a standard analysis of Eq. (3), calculating the propagation eigenmodes (analogs of Bloch modes), which grow or decay with the complex propagation wavenumber as $\exp(ik_z z) = \exp((ik_{z,\mathrm{Re}} - k_{z,\mathrm{Im}})z)$. The analysis is analogous to that performed in [7] for a pure GL modulation and in [16] for photonic crystals. The results are summarized in Fig. 2. We consider a wavelength (in vacuum) of 1 μm, a semiconductor with effective refractive index $n = 3$, a gain coefficient 10^4 m^{-1} that corresponds to $m = 10^{-4}$, and a transverse period $d_\perp = 4$ μm. The longitudinal period is $d_\parallel = 96$ μm at $Q = 1$.

It is important to note that the imaginary part of the eigenvectors, $k_{\parallel,\mathrm{Im}}$, is negative at least for one of the branches of the Bloch modes, indicating an angular range where the corresponding eigenmodes are amplified. The most efficient spatial filtering regime is characterized by a well-defined gain peak. Hence, modes propagating at small angles to the optical axis (z axis) are amplified while modes at larger angles decay or are amplified less; that is, the amplified radiation is spatially filtered. This occurs for $Q \approx 1$ and corresponds to a resonance between all three interacting harmonics [Figs. 2(b), 2(e), and 2(i)]. The branch with positive (negative) gain corresponds to a Bloch mode with intensity maxima located at gain (loss) areas of the GIM media. The third branch is a relatively homogeneous Bloch mode showing no substantial gain.

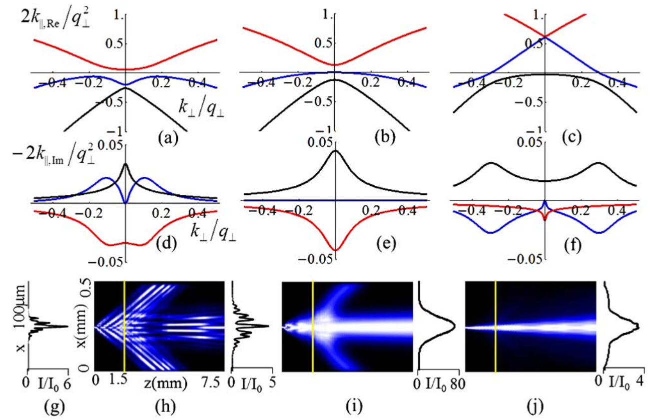

Fig. 2. (Color online) Spatial dispersion curves showing real and imaginary parts of $k_\parallel$, for (a), (d) $Q = 0.8$, (b), (e) $Q = 1$, and (c), (f) $Q = 1.6$ as obtained from Eq. (3). (g) Transverse profile of the noisy injected beam determined by a Gaussian (width 13 μm, peak intensity I_0). (h)–(j) Intensities of the propagating beam according to Eq. (1) for the three above considered values of Q. Thick vertical lines indicate interfaces between the 1.5 mm long amplifier (left) and transparent homogeneous media (right). Curves at the right side of panels show transverse field intensity distributions at the right limit of the integration domain.

At resonance, $Q \approx 1$, the dispersion curves of the three Bloch modes have a simple analytic form:

$$k_{\parallel,0} = \frac{-k_\perp^2}{2}, \quad k_{\parallel,\pm 1} = \frac{-k_\perp^2}{2} \pm \sqrt{2m^2(i + \alpha_H)^2 + k_\perp^2 q_\perp^2}, \quad (4)$$

which allows estimating the half-width of the gain peak responsible for the spatial filtering:

$$\Delta k_\perp = m\sqrt{1.5 + 6\alpha_H^2}/q_\perp. \quad (5)$$

Considering previously used parameters, the half-width corresponds to 0.5 deg inside the semiconductor media and a divergence about 1.5 deg in free space.

The dispersion curves $k_{\parallel,\mathrm{Re}}$ of Fig. 2 show concave shapes for the maximally amplified modes, indicating positive diffraction and divergent propagation behind the BAS. The situation is different for purely GL modulated materials, where convex and concave curvatures for the amplified modes are possible [7].

The numerical integration of the resonant case, $Q = 1$, shows a diffusive broadening inside the BAS with approximately a square-root dependence of the beam width on the propagated distance that evidences the spatial filtering effect. Intensity losses to sidebands are

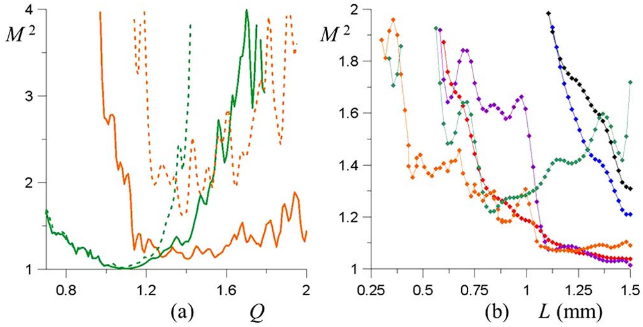

Fig. 3. (Color online) (a) Dependence of the beam quality factor on geometry factor Q for short ($L = 0.380$ mm $\approx 4d_{\parallel}$) (orange) and long ($L = 1.52$ mm $\approx 16d_{\parallel}$) amplifier (green) for random beams with initial $M_0^2 = 3.25$ (solid) and $M_0^2 = 5.07$ (dashed). (b) Dependence of the beam quality factor on the amplifier length for $M_0^2 = 5.07$ and $Q = 0.8$ (black), 0.9 (blue), 1.0 (red), 1.1 (purple), 1.2 (orange), and 1.3 (green).

always compensated by the beam amplification for $Q = 1$; intensity increases by a factor of 80 in the specific case shown in Fig. 2(i). Filtering decreases sufficiently far away from resonance. For $Q < 1$, spatial filtering is interfered with by another Bloch mode with positive gain [Fig. 2(d)], resulting in a three-peaked distribution in the far-field (or angular) domain and a modulated structure in the near field [Fig. 2(h)]. For $Q < 1$, a double-peak angular gain profile develops [Fig. 2(f)], which increases the half-width of the spatial filtering angle; also the amplified beam becomes distorted [Fig. 2(j)]. An efficient spatial filtering is obtained for $|Q - 1| \leq |\alpha_H| m/q_{\parallel}$, or equivalently $|q_{\parallel} - q_{\perp}^2/2| \leq |\alpha_H| m$, as estimated from the series expansions of propagation eigenvalues in the limit $|Q - 1| \ll 1$.

We analyze the spatial filtering effect, considering amplification of a noisy Gaussian beam [Fig. 2(h)]. A noisy beam is prepared by randomizing the phases in the spatial domain but keeping the width of the beam limited in the angular domain. Physically, this corresponds to propagation through a set of scatters with a Gaussian distribution of sizes and mean width smaller than the input beam width.

The quantitative characteristics of the filtering are summarized in Fig. 3. Behind the amplifier, the sidebands generated by the GIM rapidly separate from the central beam [Figs. 2(i) and 2(j)]. We calculate the width, W, of the central part of the beam and its divergence, θ. We numerically propagate the beam backward to reach the minimum value of the product $W\theta$, that is, to the focal plane (note that beams diverge behind the modulated BAS). At the focal plane, we calculate the beam quality factor, $M^2 = W\theta\pi/\lambda$, which has a minimum value of 1 for a perfect Gaussian beam.

Figure 3(a) depicts the beam quality factor for two different amplifier lengths and initial noise levels $M_0^2 = 3.25$ and $M_0^2 = 5.07$. M^2 reaches minimal values of 1.005 and 1.014 at $Q \approx 1.1$ for the long amplifier and 1.11 and 1.6 at $Q \approx 1.4$ for the less efficient short amplifier. The shift of the efficient filtering range to higher Q values for shorter amplifiers is related to an interplay between a broad angular gain profile and a strong beam-shape distortion induced for Q values larger than unity [Figs. 2(e) and 2(f)]. Figure 3(b) shows the beam quality factor depending on the amplifier length for different Q values. For longer structures, M^2 decreases and rapidly approaches unity. The lowest M^2 value is obtained for $Q = 1.1$ in accordance with the analytical estimate: $|Q - 1| \leq |\alpha_H| m/q_{\parallel} = 0.1$.

To conclude, we show that a spatial gain modulation in BAS amplifiers can lead to substantial improvement of the spatial structure of the amplified beam. The study is performed under realistic semiconductor parameters and technically realizable modulation periods. In particular, we show that for the proposed spatial filtering mechanism, for a single pass through a GIM BAS amplifier, a length on the order of 1 mm is sufficient for a substantial improvement of the beam quality. Beyond what is here presented, this new technique could be implemented to improve the spatial quality of emission of BAS lasers.

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