Multiple-wavelength operation of a laser-diode array coupled to an external cavity

G. C. Papen, G. M. Murphy, and D. J. Brady

Department of Electrical and Computer Engineering, University of Illinois, 1406 West Green Street, Urbana, Illinois 61801

A. T. Howe, J. M. Dallesasse, R. Y. Dejule, and D. J. Holmgren

Amoco Technology Company, 150 West Warrenville Road, Naperville, Illinois 60566

Received April 26, 1993

We report a novel geometry for coupling a laser-diode array to an external cavity that produces a diffractively stabilized lasing wavelength separation between elements of the array. The geometry allows for control of the wavelengths and wavelength spacing and provides single-knob tuning of all the wavelengths while maintaining a nearly constant wavelength offset.

The ability to generate, tune, and modulate multiple wavelengths is useful in various applications. Recent work has focused on wavelength-division-multiplexed (WDM) communications systems, but multiple-wavelength sources have potential applications in differential spectroscopy and lidar and in spectroscopic and holographic implementations of optical data storage. Bulk, integrated, and fiber-coupled WDM systems have been demonstrated in which wavelengths can be selected from an array of sources or operated simultaneously. However, some of these systems lack flexibility in the selection of wavelengths or wavelength spacing. Additionally, compensation for optical cross talk can be a significant design issue when the wavelengths share a common gain region within the WDM system.

We report a novel external-cavity geometry for an individually addressable laser-diode array wherein each element in the array is forced to lase at a unique wavelength. The wavelengths and wavelength spacing are independently selectable and exhibit single-knob tuning for all wavelengths while maintaining a fixed wavelength separation. The output beams of the cavity remain stationary during tuning, which allows for simple fiber-coupling configurations. The cavity uses a diffraction grating at grazing incidence with a curved feedback mirror retroreflecting the first-order diffraction to produce the selected wavelengths. The cavity uses common external components that allow wavelength stabilization of the entire array but maintains distinct gain regions for each wavelength to reduce cross talk and mode competition. While we present results for an integrated diode array, the geometrical construction of the cavity is flexible and would allow individual diode lasers from different material systems to be tuned together.

The external cavity is composed of a diode array, a diffraction grating at grazing incidence, and a curved feedback mirror (Fig. 1). The diode array consists of individually addressable single-stripe laser elements spaced a distance $d$ apart that are antireflection and high-reflection coated for external-cavity operation. The outputs from selected elements of the array are collimated by graded-index (GRIN) lenses so that the outputs from adjacent elements remain spatially separated through the external cavity. The individual outputs thus form separate grazing-incidence external cavities through diffraction from the grating and retroreflection from the curved feedback mirror. The combination of the diffraction angle from the grating and the curved retroreflection surface destroys the shift invariance of the system so that each diode in the array experiences a slightly different feedback wavelength. The result is that each diode lases at a wavelength controlled by the parameters shown in Fig. 1.

The lasing wavelength for each element is determined by applying ray tracing and the grating equation. To achieve efficient coupling between the guided mode in the laser diode and the external-
cavity mode, the wave vector from a single element must be normal to both the diode facet at the array and to the feedback mirror at the mirror's surface. Extending a ray normal to the diode facet from the first diode to the grating plane yields the point P shown in Fig. 1. To strike the mirror normally, the ray diffracted at point P must form an angle $\phi_1 = \tan^{-1}(x/y)$ with the grating normal, where $x$ is the distance along the grating plane from P to the center of curvature of mirror C and $y$ is the distance along the grating normal between P and C. The retroreflection requirement on the diffracted angle and the chosen angle of incidence $\theta$ determine the lasing wavelength through the grating equation $\lambda_{l} = \Lambda[\sin(\theta) + \sin(\phi_1)]$, where $\Lambda$ is the grating period. Because each subsequent channel of the array is incident at the same angle $\theta$ but is displaced in the $x$ direction along the grating by a distance $d(n - l)/\cos(\theta)$, where $d$ is the distance between the diodes, the wavelength of the $n$th channel may be written as

$$\lambda_n = \Lambda[\sin(\theta) + \sin(\phi_n)], \quad (1a)$$

where

$$\phi_n = \tan^{-1}\left[\frac{x + d(n - 1)/\cos(\theta)}{y}\right]. \quad (1b)$$

These equations may be rewritten to show the explicit dependence on the radius of curvature $r$ by using $r = \sqrt{x^2 + y^2 + q}$, where $q$ is the distance along the radius from P to the mirror. If the residual reflectivity of the front facet is sufficiently small, the tuning and offset control will be continuous with respect to the intracavity Fabry–Perot modes of the solitary laser diode, and the laser will be single mode. The wavelength jumps discretely between the solitary diode modes.

The sine dependence of $\phi_n$ in Eq. (1a) implies that the wavelength offset, $\Delta\lambda_n = \lambda_n - \lambda_{n-1}$, between diodes is not linear in $n$. These locked noncommensurate channels are useful for WDM communication systems because anharmonic channel spacings are less susceptible to nonlinear wave-mixing cross talk. The spacing and variation in $\Delta\lambda_n$ as a function of $n$ can be controlled by varying the radius of curvature of the feedback mirror or by using an aspherical feedback mirror.

There are two outputs of the external cavity per channel. The parallel output in Fig. 1 is the zeroth-order reflection of the forward-propagating beam from the array. The second output is the reflection off the grating from the beam retroreflected from the curved mirror. Because these backpropagating beams are normal to the mirror surface, the individual beams focus at a distance $r/2$, and beams combine at a distance $r$ away from the mirror. The ratio of the parallel to the combined output power depends on the type of grating and angle of incidence of the beams. The ratio is $\sim 6$ (parallel/combined) for the experimental setup used to verify the geometry. The second output is useful for monitoring or stabilizing the array when the parallel output is fiber coupled.

Because the lasing wavelength is dependent on the term $x + d(n - l)/\cos(\theta)$ in Eq. (1b), wavelength tuning can be accomplished by moving the feedback mirror in the $x$ direction. As the mirror moves, the retroreflection angle from the feedback mirror changes, thus changing the wavelength of all the diodes simultaneously. The wavelength offset is strongly dependent on the angle the incident beam makes with the grating, $\theta$, and weakly dependent on the distance from the grating to the feedback mirror, $q$. Small corrections in wavelength spacing can be made by translating the feedback mirror along the line of the principal ray, from the point where the first diode strikes the feedback mirror to point P. With this technique, the principal wavelength remains the same, and all of the other wavelengths change their position relative to this wavelength.

Verification of the lasing characteristics of the diode array coupled to the external cavity was obtained with a 28-element individually addressable diode array. The single elements are 4-µm-wide single-stripe index-guided quantum-well lasers on 250-µm-long centers with 500-µm-long cavities. Lateral index guiding was obtained via impurity-induced layer disordering$^{13,14}$ (Si diffusion) in an open-tube furnace. The core was 23% Al with a single 5-nm GaAs quantum well. The cladding was 80% Al before disordering. Without external feedback, each element was single mode. The back surface was high-reflection coated (~98%), and the front facet had an optimized multilayer dielectric antireflection coating (<0.2% over 50 nm) centered at 810 nm. Diodes at the peak of the gain of the array (~822 nm) exhibited solitary threshold currents of 8–10 mA before coating and 17–20 mA thresholds after coating. The array was mounted $p$ side up on a copper heat sink and then wire bounded to a modified 40-pin ceramic DIP package that allowed access to 20 of 28 elements in the array.

Two diodes in the array were individually collimated with 0.18-pitch, 1.8-mm-diameter single-layer antireflection-coated GRIN lenses. The external

![Fig. 2. Spectra of the two diodes with and without feedback from the external cavity. Experimental parameters: 1/\Lambda = 1800 line pairs/mm, distance between diodes 3.5 mm, x = 70.5 cm, y = 128.6 cm, $\theta = 82^\circ$, and radius of the mirror 155 cm.](image-url)
cavity was formed with a 12 mm × 50 mm 1800-line pair/mm holographic grating and an f/10 77.5-cm focal-length gold-coated mirror. The two diodes selected were 14 elements apart (3.5 mm). Solution of Eqs. (1) for the experimental parameters listed in Fig. 2 yields a calculated wavelength offset of 7.2 nm between the two diodes (0.51 nm/element).

Figure 2 shows typical spectra with and without external feedback. With the feedback mirror blocked and the current set to below threshold for each laser element, only the spontaneous emission is observed. With the same subthreshold current setting but in the presence of the external cavity, both elements lased. The wavelengths were single (solitary) mode with a measured offset of 7.3 nm. Although the wavelength difference was within the resolution limit of the spectrometer used (0.1 nm), tuning curves indicate that we have not yet achieved continuous tuning with respect to solitary cavity modes (~0.192 nm).

Figure 3 shows the peak lasing wavelength as a function of the lateral distance the mirror was moved in the x direction relative to the array and the grating. For the experimental parameters, the tuning slope (wavelength/distance) is approximately linear, and the wavelength offset is nearly constant. Both the wavelength separation and the slope of the tuning curve agree well with the theoretical slopes. The results shown in Fig. 3 indicate that, if the 13 diodes between the 2 studied could be coupled to the external cavity, they would lase at wavelengths locked to within one solitary cavity mode (~0.192 nm). Work is under way to confirm this.

In summary, we have demonstrated that a diode array can be coupled to an external cavity to produce simultaneous multiple controllable wavelengths that can be tuned together. We anticipate that such a device will have applications in WDM systems, optical memories, and spectroscopy.

References