Light beam in a heavy harness

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Lossless reshaping of multimode emission from broad-area laser diodes enables compact, highly efficient sources for a large variety of wavelengths.

Broad-area (BA) laser diodes are the most efficient light sources known and are widely used today. Kilowatts of multimode power can easily be extracted from arrays of the devices to pump fiber lasers for remote-sensing and industrial-processing applications, to give just two examples. However, owing to the planar nature of laser diodes and related optical effects, the ideal (i.e., diffraction-limited) output of each individual device cannot exceed several watts. Consequently, for higher powers, beam focus and performance are suboptimal. The current solution to this problem combines light from many laser diodes in a high-power beam using a secondary active (laser) medium such as erbium- or thulium-doped fibers. Unfortunately, it is indirect, and therefore very slow and not amenable to tuning or modulation. A compact, direct, single-mode laser diode source would bring significant advances in a number of applications that require laser beam modulation. It would also have practical ramifications for a number of unusual wavelengths that are inaccessible today. These include high-resolution, ultrafast laser radar and light detection and ranging; broadband satellite communication systems; laser high-definition TV projection; and materials processing using cutting, dicing, and marking.

The problem is not new. Numerous experiments have been conducted to force a large-emission-area laser diode to produce a single-lobe beam, and multiple solutions have been proposed. Yet mechanical cavity instabilities, low gain selectivity for high-order modes,¹ inherently low mode-gain profile overlap, and fabrication difficulties have conspired to prevent these experimental demonstrations from being converted into commercial products.

Here we describe an unusual approach for extracting spatially coherent light from a BA semiconductor laser. The laser is allowed to run in its natural high-efficiency, spatially multimode regime, and then the entire radiation pattern is converted into a single-lobe spot. The key enablers of the technique are our recent progress in laser-diode mode analysis, which clearly shows the

Figure 1. Near- and far-field spectra of BA lasers. Laser diodes: (a) type 1 at 1W output power, (b) type 2 at 2W, and (c) type 3 at 4W. The vertical axis is the wavelength (which increases from the top to the bottom of the picture). The horizontal axes are either lateral or angular coordinates. The near-field spectra are on the left side of the corresponding image group, and far-field spectra are on the right side.

stability of the mode pattern of BA devices² along with development of a low-loss spectrally resolved phase modulator.³

In recent years, we have tested various types of lasers using our four-pass spatially and angularly resolving grating spectrometer. All the broad-area lasers measured (see Figure 1 for examples) showed the box model behavior at nominal levels of power corresponding to reliable laser operation. At high power, some deviations from the box model occur. In most cases, however, they have no bearing on phase manipulation of modes. Laser samples regularly measured for more than two years exhibit no detectable variation in spatial-spectral patterns.

When modes are separated by wavelength, they can be combined using wavelength-division multiplexing. Figure 2 shows the relevant experimental setup using off-the-shelf optical components. Close to 60% conversion efficiency has been demonstrated.³ Analysis of the practical trade-offs between spectral resolution, size, and optical losses shows that a lateral-mode combining device capable of 1GHz optical resolution and 95% transmission is realizable with a physical length of less than several centimeters.

At high pumping levels, the high-order lateral modes are excited. Some of these modes can be in frequency degeneration. They are phase-independent and, therefore, not combinable. This can potentially decrease the combining efficiency for

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Figure 2. (a) An ~ 400 -channel phase mask built on a microscope slide covered with a thin layer of transparent photoresist. Precise removal of photoresist using a sharp steel needle creates 180° shifts. (b) Variation of the output spectrally integrated far fields with and without a phase mask in the spectral plane of the combining device. The narrow profile with a phase mask in the optical path corresponds to the diffraction-limited beam. a.u.: Arbitrary units.

long ($>3\text{mm}$) lasers. Active studies are currently under way to determine the spectral densities of modes in cavities of various geometries. Also, if degenerate modes are phase-locked and the locking mechanism is stable, such a group is combinable in a single-lobe pattern. For this reason, the nature and stability of the self-locking mechanism between lateral modes is an important topic for future investigation.

The work on harnessing has also provided insight into the problem of laser-diode reliability and methods of predicting it. We are currently investigating a new technique to do that based on analysis of current supplied to the laser diode. We have shown that we can recover lateral-mode spectra and even detect internal defects.⁴ We conclude that there are no fundamental obstacles to combining modes (they are not dynamically widened by nonlinear processes) and that nothing prevents us from reshaping the radiation of the BA laser into a spatially single-lobe spot, except for the apparent complexity of the external optical device. Our small-scale attempts show that such a device can be fabricated and that performance can be dramatically improved. Recent experiments we carried out with quantum cascade lasers prove that these principles can be extended to various laser geometries and wavelengths.⁵

As next steps, we intend to reduce the size of the combiner to that of a 'thick lens' (several centimeters). We also plan to optimize laser cavity geometry and light confinement to enable BA laser diodes with a low number of lateral modes. Finally, we would like to generate a compact prototype capable of delivering 10W of fiber-coupled power from a single BA element. The harnessing concept is universal to various laser types and wavelengths, and can work with laser-diode arrays, all of which suggests broad utility.

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