Photonic Integrated Circuits for High-Power Coherent Diode Lasers

BY DAVID F. WELCH

For the first time, semiconductor lasers have demonstrated single spectral and spatial mode outputs in excess of 2 W cw.[1] This milestone demonstration opens up a number of new markets that have traditionally been inaccessible for laser diodes, including space communication, high power frequency doubling, materials processing, and high resolution printing. As a measure of the significance of the 2 W cw coherent semiconductor laser, we note that the brightness of the laser diode at an output power of 2 W cw and a wavelength of 1 μm corresponds to the same brightness of a CO_2 laser operating at an output power of 200 W cw at a wavelength of approximately 10 μm. At such a high brightness, the laser diode can be incoherently coupled via brightness–conserving optics to meet the requirements of present lasers used in machining and welding systems. Although commercial diode lasers do not meet the requirements of such systems, as the problems of high power coherent operation are solved, the laser diode—by virtue of its size, efficiency, reliability, manufacturability, and accessibility to wavelengths from 0.48–4.0 μm—will continue to dramatically increase the applications base that semiconductor lasers presently enjoy. The advances that have led to the demonstration of high power coherent operation of diode lasers are closely tied to the monolithic integration of optical components and therefore indicate the diversity of applications to which integrated optics are being applied.

In this article, we introduce the topic of monolithically-integrated master oscillator power amplifiers (M-MOPA). The development of the M-MOPA has resulted in the demonstration of high power coherent, diffraction-limited operation to an output power in excess of 2 W cw in a format that is scalable to even higher output powers in the future.

High power diffraction-limited operation of semiconductor laser diodes has been pursued for over a decade. The concept to increase the power beyond that accessible from single-mode waveguide lasers was first investigated in evanescently-coupled gain-guided arrays.[2-5] Subsequently a variety of structures were studied, including gain-tailored laser arrays,[6,7] Y-junction laser arrays,[8,9] grating-coupled surface-emitting laser arrays,[10-13] and anti-guide laser arrays.[14-16] The most successful of the laser array structures has been the anti-guide laser array design, which has demonstrated output powers to 1.0 W cw in a multi-lobed nearly diffraction-limited output beam. As an alternative to the laser array structures, which exhibit multi-mode behavior at modest output powers, high-power semiconductor amplifiers have been investigated. The advantage of the semiconductor laser amplifier is the ability to extract high output powers; however the difficulty is designing the amplifier such that high power can be achieved while maintaining diffraction-limited performance. Extensive work on discrete amplifiers has been pursued by a number of groups,[17-23] originally in more of an injection-locking configuration and, as the anti-reflection coatings on the amplifiers improved, in a single-pass-amplifier configuration. Once high power diffraction-limited output from discrete semiconductor amplifiers was demonstrated, the research direction shifted to develop an appropriate amplifier design that could be integrated monolithically.[24-26] The following sections discuss the advancement of high power semiconductor amplifiers and the methods for monolithic integration.

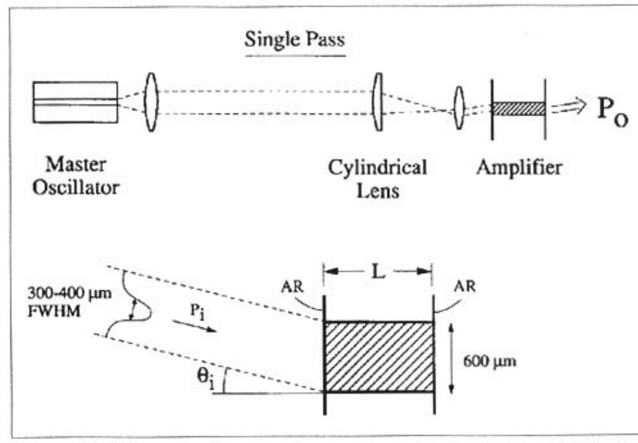

Figure 1. Schematic diagram of a master oscillator power amplifier configuration where the master oscillator and power amplifier are discrete gain elements.

DISCRETE SEMICONDUCTOR AMPLIFIERS

Due to the high power densities at the facet of the laser diode, high-power amplifiers can only be fabricated by extending the aperture of the amplifier. Larger aperture amplifiers can be fabricated in several configurations; however, we will concentrate initially on broad-area amplifiers. To achieve diffraction-limited performance from a broad area amplifier the amplifier must be designed to minimize phase distortion as the beam propagates through the active region. This requires that the distortion of the index of refraction due to charge and thermal nonuniformities be limited to quadratic phase distortions. A quadratic phase curvature can be removed using spherical optics external to the broad-area amplifier. A minimum phase distortion is achieved from a broad area amplifier through the progress made in the epitaxial growth of uniform materials, as well as the understanding of appropriate injection conditions to minimize the effects of charge on the index of refraction. In this fashion, the effects of non-uniform gain—and therefore non-uniform index of refraction—are reduced and the amplifier can be operated to a high output power before significant distortion develops in the propagating beam.

Figure 1 shows the experimental test configuration for studying discrete, 600 μm wide, broad area amplifiers. The far field patterns upon injection to the amplifier with a Ti:Al_2O_3 laser operating at 400 mW are shown in Figure 2 at output powers of 22 W pulsed and 3.3 W cw, respectively. The radiation pattern is predominantly a single diffraction-limited lobe that reflects the phase front of the injected signal with the additional quadratic curvature associated with the thermal gradients superimposed on the output beam.

The demonstration of the broad area amplifier operating in a diffraction-limited beam is the existence proof that

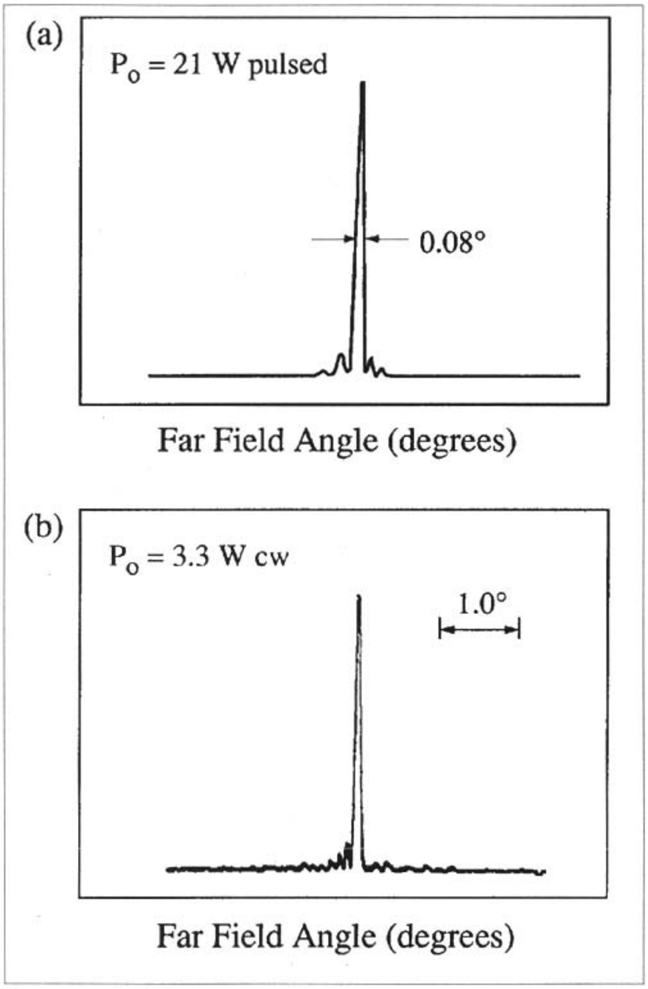

Figure 2. The far-field pattern of a discrete broad area power amplifier under injection from a Ti:Sapphire laser under (a) pulsed and (b) cw conditions at an output power of 21 W and 3.3 W, respectively.

semiconductor amplifiers can be used for high-power coherent operation. However, the necessary task is to determine the appropriate design for monolithic integration of the master oscillator power amplifier, which requires amplifiers that operate at much lower power levels from the master oscillator commensurate with that achievable from diode laser sources. One of the first demonstrations of a discrete amplifier that satisfies both the requirement of low power injection and that of narrow aperture was demonstrated by Walpole *et al.*[21] In their experiments, a high power diffraction-limited output was achieved via the injection of a laser diode operating at an output power of 30 mW coupled to a flared amplifier gain region. In this configuration, the gain of the power amplifier is tapered to match the divergence of the injected signal. As a result of the flared gain region design, the amplifier is saturated along its entire length with an injected signal of only a few milliwatts. The output power is also somewhat reduced in the flared amplifier as a result of the smaller output aperture: 200 µm for the flared amplifier compared to 600 µm for the broad area amplifiers.

M-MOPA Designs

The integration of the master oscillator with the flared power amplifier is presented in Figure 3, where the master oscillator consists of a single-mode distributed Bragg reflector (DBR) laser diode and the output of the master oscillator is injected into the flared amplifier. The DBR master oscillator is fabricated using second-order gratings for feedback to the gain region. In addition, the gain and grating regions of the master oscillator consist of a real refractive index waveguide that results in single-mode operation of the master oscillator. The spectral output of the DBR laser is defined by the grating regions and is single spectral mode over the entire operating range. The DBR laser has several additional advantages relative to Fabry-Perot lasers: the spectrum is repeatable to within 0.1 nm when the device is turned on, the spectrum is stable under modulation, the spectral linewidth is typically less than a few MHz, and the spectrum is less susceptible to optical feedback from external optical elements. All of these attributes of the master oscillator are reflected in the performance of the M-MOPA, even at the high output power of 2 W cw.

As the light exits the master oscillator, the beam diffracts as it propagates through the amplifier. Thus, the charge is used efficiently, resulting in a high differential efficiency, and the output power is increased such that the propagating beam maintains (nominally) a constant power density as the diffracting beam aperture increases. The total output power is therefore increased linearly along the length of the amplifier. The actual intensity distribution differs from this simplistic view as a result of self-focusing induced by residual non-uniform charge distribution and thermal variations in the amplifier region. The light exits the amplifier through an anti-reflection coated cleaved facet. The emitted beam is a single-lobe far-field characteristic of the source diffraction from the single-mode waveguide of the oscillator when propagated through a medium that acts as a spherical lens resulting from the thermal and charge distribution within the active region.

The radiation pattern, after the quadratic phase curvature of the amplifier is removed, is presented in Figure 4. The far-field pattern is a single lobe, nominally diffraction-limited, that does not steer or change in width to a maximum output power of 2 W cw. The operation of the M-MOPA to a power of 2 W cw is the first demonstration of a semiconductor laser operating in a single diffraction-limited lobe to an output power greater than 0.5 W cw, and is the starting point for a new class of semiconductor laser diodes. The far-field pattern has also been characterized by an M^2 measurement where values of 1.5 have been measured that are independent of power. As a test of the beam quality of the M-MOPA, the output has been coupled to a $KNbO_3$ crystal for single-pass frequency doubling, resulting in greater than 2 mW of blue light for 500 mW of infrared light input.

As discussed above, the spectral output of the M-MOPA reflects that of the master oscillator and is single-mode throughout its operating range. When the M-MOPA is operated such that the master oscillator current is constant and the output power is varied through changes in the drive current to the power amplifier, the spectrum remains nearly constant. In the case where the amplifier power varied from 0-2 W cw the residual heating of the oscillator results in less than 0.1 nm change in the emission wavelength. As a result, the M-MOPA output is very stable over its entire operating range. This is advantageous for frequency doubling, coherent communications, and coherent ranging.

One of the many virtues of the M-MOPA design is the ability to modulate the source with small current changes to the master oscillator. As shown in Figure 4, when the current to the oscillator is turned off, the power in the far-field lobe is reduced by greater than 25 dB. Therefore, the full 2 W output can be modulated via the 150 mA current to the master oscillator. This is highly advantageous since high speed modulators are typically low power devices.

The characteristics discussed above, including the first demonstration of a semiconductor laser at a diffraction-limited output power of 2 W cw, are just a few of the many desirable features of the M-MOPA. The advances realized in the M-MOPA are a culmination of technologies that have been developing since the early 1980s, and its impact on high power coherent sources for printing, frequency doubling, and communication will last well into the next decade.

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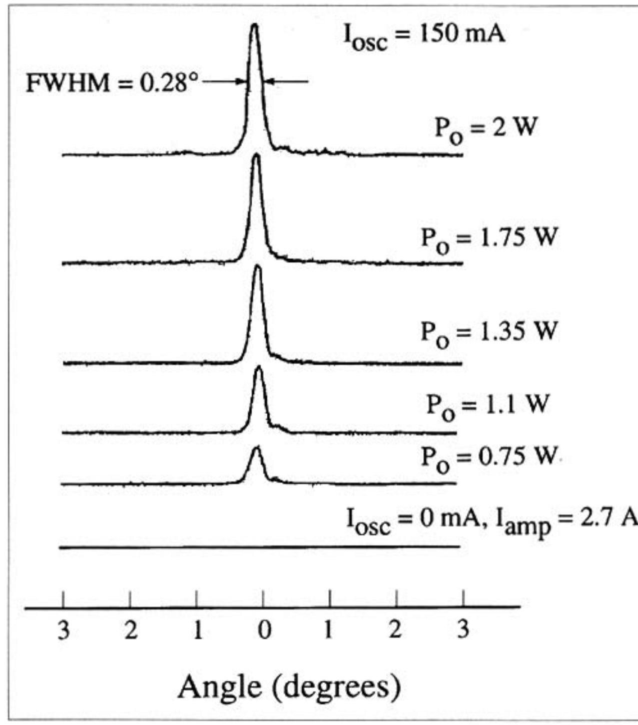

Figure 4. The far-field pattern is presented as a function of output power, demonstrating the single diffraction-limited lobe pattern to an output power of 2 W cw.

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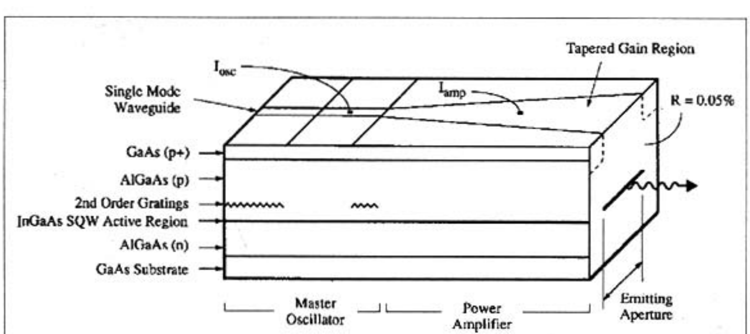

Figure 3. Schematic diagram of a monolithically integrated master oscillator power amplifier (M-MOPA).

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