Spectral shaping of a 10 W diode laser-Yb-fiber amplifier system

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We describe a continuous-wave master-oscillator power-amplifier system based on a distributed Bragg reflection diode laser and an Yb doped fiber amplifier. The observed optical spectrum of the amplified seed source can be tailored to arbitrary shapes and widths between 30 MHz and greater than 1 GHz by controlling the radio frequency modulation wave form of the injection current.

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I. INTRODUCTION

The efficient optical pumping of an atomic vapor under ambient pressure requires lasers with high average output power at the wavelength of the atomic transition. Nevertheless, the optical pumping efficiency remains strongly dependent on the spectral shape of the laser line, as has been theoretically described.¹ So far excitation experiments have used unspecific broadening of the laser line [e.g., through rapid frequency modulation (FM)] that coarsely matches the overall spectral width of the atomic transition.^{2,3} No attempt was made, however, to generate a suitable shape of the laser line. An example is the optical pumping of ³He at around 1080 nm,⁴ where medical applications or application such as neutron spin polarizer require the excitation of large volumes with maximum efficiency. In this case, to match the Doppler broadening of the He transition a high-power laser light with a Gaussian line shape is required. Simple frequency modulation, although straightforward to implement, results in a spectral distribution, which does not match the Gaussian profile of a Doppler-broadened spectral line,¹ preventing optimum pumping efficiency from being achieved. Even so, this has been used to demonstrate improved efficiency over pumping with narrowband sources.²⁻⁴ Clearly, however, a Gaussian spectral distribution would lead to further efficiency enhancements. Several designs of all-fiber master-oscillator power-amplifier (MOPA) systems have been investigated to the 5 W level,⁵ and high-power fiber oscillators have been investigated to the 10 W level; however, imposing a particular spectral shape or even an appropriate overall bandwidth remains difficult.

In our previous work, aimed at nonlinear conversion into the midinfrared, we demonstrated a single-stage, high-power diode-fiber MOPA system, which is continuously (mode-hop-free) tunable over a range 110 GHz.⁶ However, its low (maximum a few hertz repetition) tuning speed excludes spectral tailoring as required for efficient optical pumping of

Doppler broadened transitions. This has led to the investigation of rapid modulation of lasers generating arbitrary average spectral distributions.

In the present work, the modulation properties of a single-stage diode-fiber MOPA system that emits 10 W of cw output power at a wavelength around 1080 nm are described. The 30 MHz laser bandwidth is rapidly modulated with various temporal functions to produce optical spectra with various shapes. The direct current modulation of the distributed Bragg reflection (DBR) diode laser oscillator by three examples of modulation functions, namely, sinusoidal, triangle, and inverse hyperbolic tangent, results in spectra resembling a U shape, a rectangle, and a Gaussian, respectively. The limitations on the spectral shapes due to the effect of amplitude modulation (AM) originating from the direct current modulation of the diode laser current are also discussed.

II. EXPERIMENTAL SETUP

The schematic setup of the diode-fiber MOPA system is shown in Fig. 1. The master oscillator is a three-section DBR diode laser⁷ with a threshold current of 80 mA. After passing the output of the laser through two 30 dB isolators the maximum available power is 30 mW, obtained at a drive current of 150 mA to the gain section. The structure of the diode laser⁸ comprises sections for gain, phase control, and DBR feedback. The latter two are fitted with resistive microheaters to allow thermal tuning of the output wavelength at frequencies of tens of hertz. By simultaneous and synchronous control of the resistor currents, up to 110 GHz of continuous tuning could be achieved,⁶ thus providing a means to tune the center wavelength of the laser to spectral lines of interest in pumping applications. This tuning mechanism is, however, too slow to achieve the frequency modulation at megahertz levels required for spectral broadening and shaping.

In normal operation, the tuning currents for the phase and DBR section heaters are derived from sources floating with respect to the anode and cathode connections to the gain section. This ensures that the tuning currents flow only through the heating resistors and the diode junction in these

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FIG. 1. Experimental setup: DBR diode: distributed Bragg reflection diode laser with independently controlled gain section (ga), phase section (ph), and grating section (DBR); 60 dB: double-stage Faraday isolator with 30 dB isolation each; Yb fiber: 36 m Yb-doped double clad fiber; DM: dichroic mirror and pump diode: 25 W at wavelength of 976 nm.

sections remains unbiased. However, connection of the tuning current terminals to a supply having a common ground with that of the gain section allows biasing of the phase or DBR sections in the same manner as the gain section.⁹ With our device, it was found that modulation via the phase-section bias current, in this manner, could be achieved with higher bandwidths than via the gain section. To achieve this, a dc bias and high-frequency modulation currents were applied to the phase section via a bias tee. A dc bias of 45 mA was used to ensure high-frequency modulation took place in a forward biased, and therefore approximately linear, regime. This also had the effect of reducing the gain section current at threshold and increasing the maximum output power, after isolation, to 45 mW. The output spectrum under various modulation conditions was measured using a 3 GHz free-spectral range confocal Fabry-Pérot interferometer. In the absence of modulation, a spectral width of 30 MHz was measured, limited by the interferometer resolution.

For sinusoidal modulation a signal generator (Marconi 2022) was used to provide the driving rf wave form. A fast arbitrary wave form generator (AWG 2021) was utilized to produce complex wave forms. The arbitrary wave form generator can be programmed with analytical expressions to obtain the desired wave forms. The repetition frequency of the wave form was chosen such that, after digital-to-analog conversion (1024 pixel window with 1.024 GHz clock frequency), it generated the wave form in multiples of 8, so that unwanted Fourier components are suppressed. In front of the amplifier 40 mW of modulated output from the diode oscillator was available.

The amplifier consisted of a 36 m long Yb doped double-clad large mode area (LMA) fiber.¹⁰ The active core has a diameter of 10 μm , a numerical aperture (NA) of 0.07, and is doped at a concentration of 1000 mol ppm. The D-shaped inner cladding with a 400 μm diameter and a NA of 0.38 is end pumped by a 25 W fiber-coupled (400 μm diameter and a NA of 0.22) broadband diode laser at 976 nm.

III. RESULTS

First, the power of the amplified diode radiation as a function of pump power was measured. For these measurements the modulation wave form was an inverse hyperbolic

FIG. 2. (a): Output power of the diode-fiber MOPA system vs in-coupled pump power. Inset shows the arctanh modulation applied to the DBR diode laser at ω_m (frequency) = 16 MHz. (b) Power spectrum of the amplified output showing >50 dB ASE background suppression, when the MOPA system operates at maximum output power. Inset shows the Gaussian-shaped diode laser spectrum, resulting from the modulation depicted in inset (a), with $\Delta\nu_L = 90$ MHz at $I_{ff} \sim 0.85$ mA.

tangent with a repetition frequency of 16 MHz and a rms current around 0.85 mA. This resulted in an average optical spectral distribution that was Gaussian in nature with a 90 MHz bandwidth [full width at half maximum (FWHM)] as shown in Fig. 2(b). Figure 2(a) shows that the maximum output is 10 W for a maximum in-coupled pump power of 19 W. The maximum slope efficiency was 55%. Beyond a pump power of 5.5 W, the output power increases linearly with pump power indicating that the fiber amplifier was saturated. The spectral density of amplified spontaneous emission (ASE) is suppressed by more than 50 dB with respect to the amplified diode radiation, and the total ASE power is less than 1% of the total output power as shown in Fig. 2(b). The output power is stable, independent of pump power, over long periods of time with less than 10^{-3} fluctuation over a period of hours. This indicates that pulsing due to stimulated Brillouin scattering, common in fiber amplifiers,⁵ was effectively suppressed¹¹ by the spectral broadening achieved through modulation.

FIG. 3. Optical spectral properties of the diode with modulation of the diode's phase section current. (a1) Sinusoidal modulation at $\omega_m=20$ MHz and $I_{rf}=7$ mA. (a2) The asymmetry between the peaks for sinusoidal modulation increases with laser bandwidth. (b1) Triangular modulation at $\omega_m=16$ MHz and $I_{rf}=0.85$ mA. (b2) Best fit of ripple shows linear increase for triangular modulation with laser bandwidth. (c1) Inverse hyperbolic tangent modulation $\omega_m=16$ MHz and $I_{rf}=5$ mA and (c2) root-mean-square deviation from Gaussian spectrum (χ^2) as a function of laser bandwidth.

The spectral distribution of the laser was characterized for three different current modulation functions. When the laser is modulated with a 20 MHz sinusoidal function, a U-shaped distribution is expected because the amount of time the modulation current $I(t)$ spends in the I and $I+dI$ (which determines the laser frequency) is greatest at the extrema of the modulation current. Thus the output power at the frequencies associated with peak and minimum current will be greatest.¹² An example of a U-shaped spectral distribution is shown in Fig. 3(a1), in this case a rms current of 7 mA was employed and the distance between peaks was 1.8 GHz. The distance between the peaks of the spectral distribution increased by 280 MHz/mA rf current amplitude. The asymmetry observed in the spectral distribution is due to

amplitude modulation of the laser output power.¹³ Figure 3(a2) shows the asymmetry between the peaks as a function of the peak separation. The asymmetry becomes larger with higher modulation currents; it is 4% when spectral width is around 150 MHz and it increases linearly to around 35% at a spectral width of 1.8 GHz.

A rectangular spectral distribution can be achieved by triangular modulation. In this case the amount of time $I(t)$ spends in the current interval from I to $I+dI$ is the same for all I so the laser should emit with equal power at all frequencies covered by the modulation period. Figure 3(b1) shows a 120 MHz broad spectral distribution resulting from 16 MHz triangular modulation function with a peak current of around 0.85 mA. The influence of amplitude modulation is more

significant in this case leading to asymmetric ripple in spectrum that increases with the width of the spectrum, as shown in Fig. 3(b2). The best fit to the ripple, which is a measure of deviation from the rectangular spectrum, increases linearly with spectral bandwidth at a rate of 0.1% /MHz reaching 50% at 500 KHz.

As was described earlier,¹² modulating the diode current with an inverse hyperbolic tangent function should lead to a Gaussian spectral distribution. This can again be understood in terms of the time spent by $I(t)$ in the current interval from I to $I+dI$. The inverse hyperbolic tangent changes slowest when I is near zero, thus maximum power is emitted in the center of the spectrum. The derivative of $I(t)$ goes to infinity at the current maxima and minima, thus decreasing power is emitted with increasing distance from the center of the spectrum. Figure 3(c1) shows the optical spectral distribution obtained when modulating the diode with a 16 MHz inverse hyperbolic tangent with a peak current of 5 mA along with a Gaussian fit. Again the spectral distribution is slightly distorted on one side, which can be attributed to amplitude modulation seen as an emerging peak. The peak grows in height with increasing modulation current. Beyond a spectral width of 500 MHz shown here, the deviation from a Gaussian is obvious. The amount of root-mean-square deviation of the experimental data from the Gaussian shape, given by χ^2 , is plotted against the measured spectral bandwidth. The inset graph of Fig. 3(c2) shows that as the depth of modulation is increased, the deviation from a Gaussian shape increases. The residual oscillations during this increase could be attributed to a small drift of the 3 GHz Fabry Prot monitoring interferometer. For bandwidth values less than 550 MHz it can be seen that χ^2 values are less than 0.1 such that the experimental spectra closely resemble a Gaussian shape.

The amplitude modulation induced distortion of the observed spectral distribution is more pronounced for triangular and inverse hyperbolic tangent wave forms than for sinusoidal modulation [Fig. 3(a)]. This, in part, may be due to distortion introduced by digital-to-analog conversion of the

arbitrary wave form generator. We note that the spectral distributions of the amplified diode output (10 W) are found to be the same as before amplification, irrespective of what particular modulation function is used for spectral shaping.

In summary, we have presented the first diode-oscillator fiber-amplifier (MOPA) system that offers spectral shaping and high output power around 1080 nm. The diode laser is a three-section DBR diode, with dc bias at the gain section. In addition, the phase section is driven independently with a rf arbitrary wave form superimposed on a dc current to shape and broaden the narrowband laser bandwidth to greater than 1 GHz. The effect of modulation by different rf wave forms on the diode spectrum was investigated in three examples, and it was found that the spectral distribution could be controlled via the rf wave form. The diode power of 40 mW was amplified in an Yb doped fiber, which retains the oscillator spectral characteristics at 10 W level powers, and with high (50 dB) suppression of ASE spectral background. Simultaneously the rf modulation removes a spiking of the output and leads to a power stability (better than 10^{-3}) over hours.

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