

Multiwavelength Mode-locked InGaAsP Laser Operating at $12 \text{ ch} \times 2 \text{ GHz}$ and $16 \text{ ch} \times 10 \text{ GHz}$

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Abstract—In this letter, we report on the development and characterization of an InGaAsP semiconductor optical amplifier-(SOA) based ring cavity laser that emits up to 16 wavelengths in the 1550-nm region. The laser is loss modulation mode locked at up to 10 GHz with temporal pulses of ~ 25 ps. Spectral control of the emission is accomplished by an intracavity 4-f spectral pulse shaper with a programmable liquid crystal spatial light modulator (SLM) in the Fourier plane. Voltage control of the transmissibility of the pixels of the SLM defines the wavelength channels and allows flattening of channels to produce a uniform intensity of channel outputs.

Index Terms—Mode-locked laser, multiwavelength laser, semiconductor optical amplifier, spatial light modulator, wavelength-division multiplexing.

I. INTRODUCTION

WAVELENGTH-DIVISION MULTIPLEXING (WDM) in telecommunication and data transmission systems increases system capacity by more fully taking advantage of the intrinsic bandwidth of installed optical fiber. Channel widths and spacings have been standardized so those necessary system components such as lasers and spectrally dispersive components can be designed for interoperability. Simultaneously, the data rate of individual channels is being pushed toward higher rates with ~ 10 -Gb/s standards (both Sonet and Ethernet) near deployment. Current architectures utilize a separate laser for each wavelength channel introducing complexity and cost issues. Significant research has been conducted to develop and assess potential multiwavelength sources for WDM systems. Multiple active device arrays of both laser diodes and vertical-cavity surface-emitting lasers (VCSELs) have been constructed and tested, but problems with growth control toward exact spectral emission remains a concern [1]. Continuum generation in optical fibers from high-power pulsed sources followed by spectral filtering has been demonstrated, but suffers from the need for the high-power front end, as well as the power inefficiency of discarding much of the generated spectrum in the filtering process [2]. Multiple quantum-well devices with individually shifted spectral gain have also been constructed and also utilized downstream spectral filtering with the attendant power inefficiencies [3]. Cavities based on various grating technologies [4], [5] and erbium fiber ring cavities with distributed fiber gratings or etalons have also been demonstrated [6]–[8].

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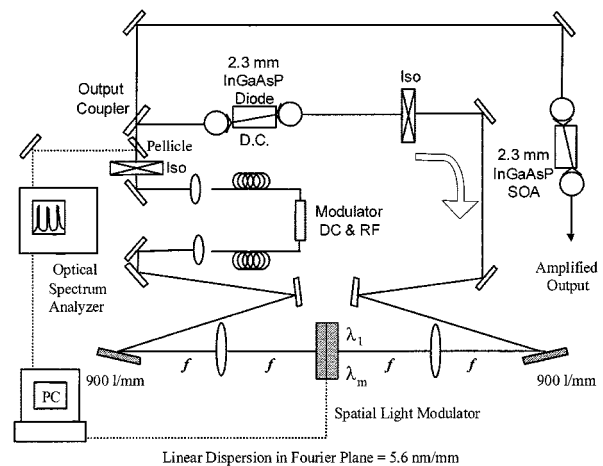


Fig. 1. SOA mode locked ring laser system with spatial light modulator for spectral control.

This work expands upon previous efforts utilizing external cavity oscillators based on semiconductor optical amplifier (SOAs) at both 850 and 1550 nm [9]–[12]. The intracavity inclusion of a spectral pulse shaper allows selection of the particular wavelengths allowed to oscillate while active mode locking, either gain or loss modulation, insures gain available over the whole amplified spontaneous emission (ASE) width of the SOA. Previous work used a simple spatial mask of lines and spaces to define the spectrum. In this work, a liquid crystal spatial light modulator (SLM) is employed to significantly increase the spectral control of the laser. SLMs have been used to significant advantage in managing spectral channels for WDM systems and have also been used for gain equalization of amplifiers in the spectral region of telecom interest [13], [14], but this is to our knowledge the first use of a SLM intracavity to actively control the spectrum of a multiwavelength oscillator.

II. LASER CONFIGURATION

The laser configuration is shown in Fig. 1. A unidirectional ring cavity is comprised of a 2.3-mm multiple quantum-well (MQW) InGaAsP SOA with conventional bulk optics, Faraday isolators, a PM-fiber-pigtailed Mach–Zehnder intensity modulator and a dual grating 4-f spectral pulse shaper intracavity with the liquid crystal SLM installed in the Fourier plane. The cavity's fundamental mode-locking frequency is ~ 47.784 MHz, while active modelocking at either 2 or 10 GHz was achieved through high-speed loss modulation at the 43rd and 211th cavity harmonics (2.054 and 10.0825 GHz, respectively).

The spectral control of the cavity is performed by the SLM. Dual 128 linear pixel arrays are mounted back to back. The ap-

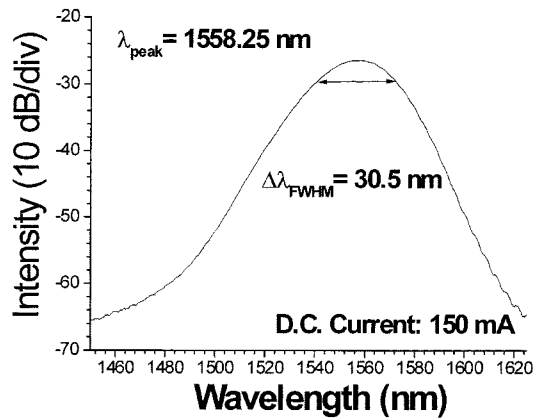


Fig. 2. ASE spectral curve of the 2.3-mm InGaAsP MQW SOA.

plied voltage to each pixel determines its retardance with transmissibility and phase of each pixel position being functions of the combined retardances of the two arrays. The pixel pitch is 100μ (97μ active with a $3\text{-}\mu$ guardband). The gratings used are gold-coated 900 l/mm holographics, while the lenses are plano-convex Pyrex singlets of 150-mm focal length. The result is a spectral dispersion in the Fourier plane between the lenses of 5.6 nm/mm. The spectral control leg is installed before the loss modulator (wrt direction of the ring) to provide the maximum beam size on the initial grating to maintain best resolution spot size in the plane of the SLM.

A second 2.3-mm SOA provides single-pass amplification after which the pulse train is fiber coupled and either detected by a high-speed photodiode for temporal pulse measurements via oscilloscope, or directed to an optical spectrum analyzer. Note that a pellicle beam splitter is installed intracavity to allow spectral monitoring of the oscillator's behavior. An additional diagnostic available is a second-harmonic generation (SHG) autocorrelator since the generated pulse duration is equivalent to or shorter than the impulse response of the detector and sampling head of the oscilloscope.

III. LASER PERFORMANCE

As the baseline of spectral performance, Fig. 2 shows the ASE spectrum of the diode at the heart of the oscillator. Threshold dc bias to the diode for continuous-wave (CW) lasing was 110 mA with the modulator fully transmissive ($V\pi = 4.0$ Vdc). For mode locking, the modulator was rebiasd (2.0 Vdc) to a point of approximately half transmission and RF power of +27 dBm was applied at the desired mode-locking frequency. The laser was mode locked at 2 GHz with the SLM adjusted to full transmissibility across all pixels producing an optical spectrum of 4.5-nm full-width at half-maximum (FWHM) and pulses of 15 ps (deconvolved Gaussian, ~ 19 times transform limit) as measured by SHG autocorrelation. Spectral channels are then defined by setting the transmissibility of two adjacent pixels to maximum and the flanking pixels to minimum. This pattern is repeated for the number of desired channels, 12 in this case. The dc bias current to the SOA was increased to 180 mA to provide higher gain across the available spectrum.

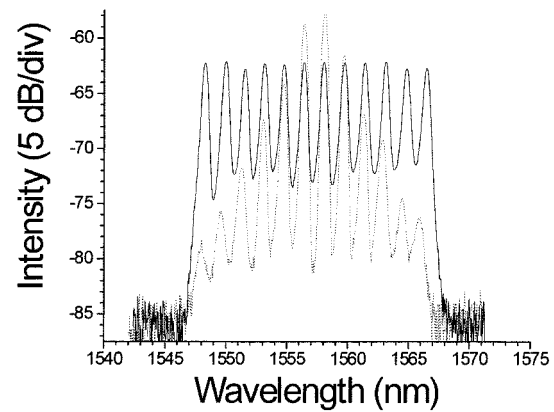


Fig. 3. Multiwavelength spectrum from oscillator with two pixels fully transmissive and adjacent pixels blocking for 12 channels. Dotted curve before spectral flattening, solid curve after spectral flattening. Mode locked at 2 GHz.

The result is multiwavelength pulsed output with the relative amplitude of the channels reflecting the ASE gain curve of the diode as shown in Fig. 3. Time averaged power of the oscillator output was 38.9μ W. Note that the channels separation of ~ 212 GHz (1.68 nm) as defined by the pixel pattern corresponds with the linear dispersion calculated for the Fourier plane.

The transmissibility of the pixels of channels with the greatest intensity is then progressively reduced resulting in not only lowered intensity for those channels, but increased intensity of the weaker channels due to the homogeneously broadened nature of the gain medium. The process of gain flattening was initially done manually. An improvement to the laser utilizes the general purpose interface bus (GPIB) ports of the SLM controller and optical spectrum analyzer in conjunction with Labview software to form a closed loop controller over the flatness of the optical spectrum peaks. The optical spectrum analyzer is scanned to determine the power levels of the multiple channel peaks and an arithmetic average of the peak values calculated. The software then determines new voltage levels to write to the SLM decreasing the transmissibility of channels above the average. This process iterates until channel flatness falls within the available intensity change associated with a single bit level voltage change to the SLM (~ 10 bits over a 10 Vdc range). The relative amplitude of the channels after convergence is shown in Fig. 3. Gain flattening does sacrifice overall output power of the oscillator. Measured output power was reduced to 30.25μ W, a loss of 1.09 dB compared to the initial unflattened output. Operating multiwavelength broadens the temporal pulses to 25 ps (deconvolved Gaussian). The autocorrelation and optical pulse train are shown in Fig. 4. Note that with individual channel widths of ~ 0.75 nm, a time bandwidth limited pulse would be ~ 4.5 ps and the multiwavelength pulses are 5.5 times transform limit. Active mode locking of external cavity SOA lasers typically produces a linear chirp which can be compressed to yield time bandwidth products much nearer the limit ($\sim 1.2\text{--}1.3$) [15], but no attempt is made to compress here and the autocorrelation shows coherent pikes from the multiple lines of operation. Loop iteration time is dominated by the settling time of the liquid-crystal pixels (~ 600 mS), the read cycle time for scanning the peaks from the optical spectrum analyzer (~ 500 mS) and determining new

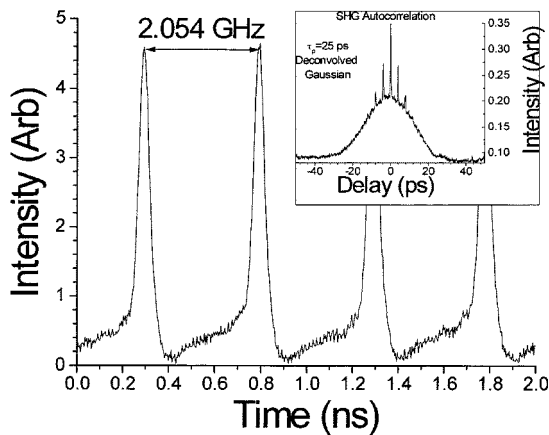


Fig. 4. Multiwavelength pulse train and autocorrelation after spectral flattening.

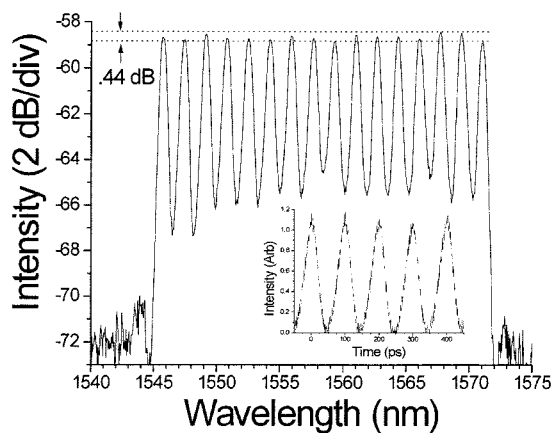


Fig. 5. Multiwavelength spectrum for 16 channels at 10 GHz after spectral flattening.

voltage values for the SLM pixels based on a calibration lookup table. Convergence to steady state with amplitude variance between channels typically less than 0.5 dB occurs in 100 iterations or less.

Increasing the bandwidth of the RF components employed, the laser was modulated at a nominal 10 GHz and the number of channels increased to 16 to yield a net bit rate for a hybrid TDM-WDM transmission system of ~ 160 GHz. The optical spectrum of channels is shown in Fig. 5. The maximum intensity difference between channels is less than 0.44 dB. Average contrast is reduced as the number of wavelengths is increased. In the 12-channel case, the contrast is ~ 10 dB, whereas in the 16-channel case, this value has fallen to ~ 8 dB. Contrast can be improved for this system overall by insuring that the resolution spot size in the Fourier plane is less than or equal to the pixel size of the SLM. In this case, the resolution spot size was calculated to be ~ 1.25 times the pixel size based on available lenses and grating. The 10-GHz pulse train is also shown in Fig. 5. Autocorrelations on these pulses show a further temporal pulse broadening to 29 ps.

IV. CONCLUSION

We have demonstrated the ability of a single InGaAsP semiconductor optical amplifier to emit multiple wavelengths appro-

prate for WDM system applications when configured as a high frequency mode-locked external cavity oscillator. Spectral definition and control is accomplished by a SLM in the spectrally dispersive Fourier plane of a 4-f spectral pulse shaper and the spectral width available for line generation is approximately as broad as the FWHM of the spectral gain curve of the diode. Intensity flatness of the multiple spectral lines is achieved through adjusting the transmissibility of individual SLM pixels. Combining spectral monitoring of the laser output with the SLM controller in a closed loop configuration yields excellent control over the lasers spectral behavior.

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