Multi-Wavelength Arrays of Mode-Locked Lasers for WDM Applications

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ABSTRACT

The continued need for increased bandwidth is driving the pursuit of both increased speed in TDM and more channels in WDM for fiber optic communication systems. Multiwavelength arrays of monolithic mode-locked DBR lasers are an attractive source for future high bit rate (100-800 Gb/s) optical communication systems. Monolithic mode-locked lasers in the colliding-pulse mode-locked configuration have been fabricated, with DBR end mirrors for wavelength selection. A continuous gain region has been employed for ease of fabrication and the elimination of multiple reflections within the cavity. Arrays containing up to 9 wavelengths have been fabricated, with all the wavelengths within the erbium-doped fiber amplifier gain bandwidth. An RF signal is applied to the saturable absorber for synchronization to an external clock and reduction of the phase noise. For a 4.6 mm cavity, short (< 10 ps) optical pulses at high (~18 GHz) repetition rates have been achieved. Low single side-band phase noise values (-107 dBc/Hz @ 100 kHz offset) have been demonstrated, nearly equal to that of the RF source.

1. INTRODUCTION

The need for increased bandwidth is driving the development of both increased speed in time division multiplexing (TDM) and more channels in wavelength division multiplexing (WDM) for fiber optic communication systems. While present WDM systems utilize discrete DFB lasers, future high speed systems would greatly benefit from a stable, integrated source of optical pulses at very high repetition rates for soliton communications. Mode-locked lasers are a potential source at high repetition rates (>10 GHz), where monolithic cavities can be easily fabricated with reasonable cavity lengths (<5mm). In our work, the colliding pulse mode-locked (CPM) configuration for the mode-locked lasers has been chosen due to the prediction[1] and demonstration[2] of stable, short pulse output in both passive and hybrid configurations. Singular CPM devices have been used successfully in transmission systems[3]. We have extended previous work on CPM lasers to multi-wavelength laser arrays, where the center wavelength of each device is adjusted by a DBR grating in the cavity.

2. DEVICE FABRICATION

The monolithic CPM laser is fabricated using two MOCVD growths. The first growth is a separate confinement heterostructure with 4 compressively strained (ε=1%) quantum wells at 1.55 μm and confined on either side by 1200 Å of InGaAsP (λ=1.2 μm). After the diffraction gratings were written by direct write electron beam lithography and etched into the SCH region, the upper cladding and contact layers were grown. The lasers were fabricated into a 3.5 μm wide ridge laser structure with a continuous active region, and arrayed on 250 μm centers for compatibility with silicon-based fiber v-groove arrays. As seen in Fig. 1, the symmetric 4.6 mm long ridge was divided into 5 sections with 3 contacts: the two end sections are 75 μm each and contain the gratings; the two gain sections are 2180 μm; and a center saturable absorber section of 50 μm. The sections are separated by four 10 micron gaps, and electrical isolation of ~ 1kΩ is achieved between the sections by etching the InGaAs contact layer. The fabrication of microwave ground-signal-ground (GSG) contacts for the saturable absorber (with an on-chip via to the *n*+ substrate) allows for high frequency probing. A continuous gain region has been employed for ease of fabrication and the elimination of multiple reflections within the cavity. However, the presence of gain material in the grating region places an upper limit on the current that can be applied to the grating section (lest the grating region lase as a DFB on its own).

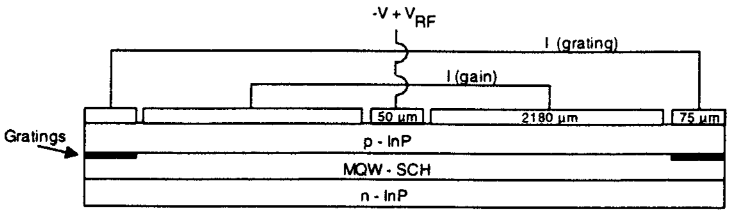


Fig. 1 Schematic diagram of the symmetric 4.6 mm mode-locked laser cavity.

3. DEVICE PERFORMANCE

The threshold current for uniformly pumped devices without gratings is approximately 120 mA; devices with gratings show thresholds of 135 - 155 mA (when all the contacts are shorted together). A typical CW L/I measurement is shown in Fig. 2 for several values of saturable absorber voltage. When a reverse bias is applied to the saturable absorber, the devices exhibit passive mode-locking for a range of gain currents and saturable absorber voltages. Typical operating currents are in the range 165-210 mA and typical saturable absorber voltages are –0.5 to –2.0 volts. The devices mode-lock best near threshold (as seen by Chen and Wu[2]), and have facet powers of ~ 1mW at the optimal operating points. The 4.6 mm device has a fundamental mode spacing of 9.027 GHz; when operating as a CPM laser, the pulses are emitted at 18.054 GHz.

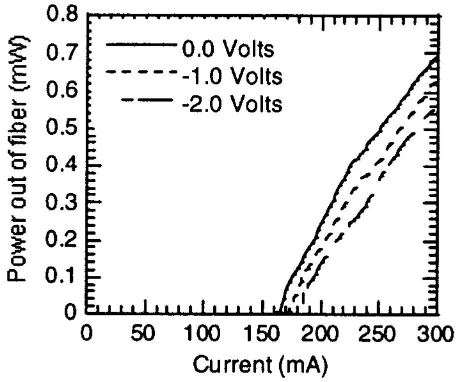
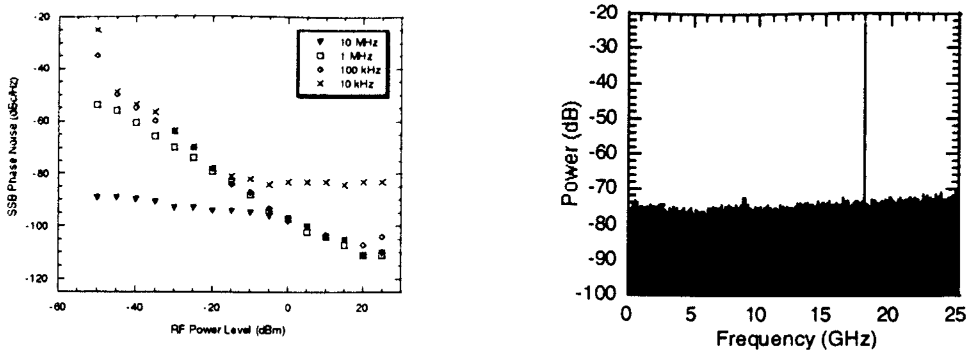


Fig. 2 A typical CW L/I measurement for different values of saturable absorber voltage.

The spontaneous emission fluctuations which start the mode-locking lead to random shifts of the carrier frequency and large phase noise and timing jitter. This noise in passive mode-locked lasers prevents their use for optical communications[4]. A bias tee attached to a high frequency probe is used to supply both the DC reverse bias and a sinusoidal clock signal at 18.054 GHz to each of the devices to reduce the phase noise and jitter. Phase noise measurements close to and far from the carrier as a function of the applied RF power have been completed, and all the devices show a sharp reduction in the single side-band (SSB) phase noise and a suppression of the cavity fundamental resonance with an increase in the applied RF power (Fig. 3(a,b)). At 20 dBm input power and 100 kHz offset, the SSB phase noise is as low as -107 dBc/Hz, within 1 dB of the RF source (HP 83731B + 8349B amplifier).



(a) (b)

Fig. 3 (a) The reduction in the SSB phase noise with the increased application of RF clock power at different offsets from the carrier. The RF source has a baseline SSB phase noise of -83, -108, -122 and -122 dBc/ Hz at 10 kHz, 100 kHz, 1 MHz and 10 MHz offset from the carrier, respectively. (b) RF spectrum analyzer output, showing greater than 30 dB suppression of the fundamental cavity resonance.

Jitter measurements in mode-locked lasers typically follow the technique[5,6] in which the higher order harmonics of the mode-locked signal are measured on a spectrum analyzer and the phase noise is integrated over a frequency range around the harmonic signal; however the high repetition rate of these devices precludes such a measurement with our instrumentation. An estimate of the phase noise was obtained by integrating up the phase noise around the fundamental signal at 18.054 GHz from 10 kHz to 10 MHz offset to obtain $\sigma_{rms} < 0.15$ ps (compared to the source alone, which had $\sigma_{rms} < 75$ fs in this same frequency range).

Fig. 4 shows the modulation response of the CPM lasers under mode-locking conditions. Outside the mode-locking regime of operation, the RF spectra shows a distinct peak at both the cavity fundamental of 9.027 GHz and at the mode-locking frequency of 18.054 GHz. Under the proper bias conditions, the device mode-locks at 18.054 GHz with removal of the CW component, and the 9.1 GHz peak is strongly (> 30 dB) suppressed.

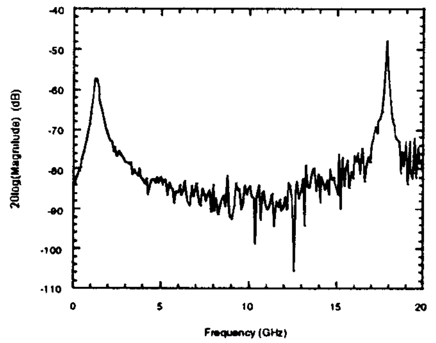


Fig. 4 The modulation response of the mode-locked laser showing the complete suppression of the fundamental of the cavity at ~ 9 GHz .

We have demonstrated a 5 element array with wavelength separation between devices for 5 ps pulsewidths. For a transform limited 5 ps optical pulse at 1.55 μm, the required FWHM spectral bandwidth is 0.63 nm (79 GHz @ 1.55 μm) assuming a sech^2 shape[7]. The 20 dB down spectral bandwidth is then 2.5 nm (313 GHz). To conform to the multiples-of-100 GHz ITU standard, the wavelength channels for the devices were designed to have the next larger spacing, which is 3.2 nm or 400 GHz. The combined optical spectra of the five element array is shown in Fig. 5 with no current tuning, with an average channel spacing of 3.3 nm. All wavelengths are compatible with the erbium doped fiber amplifier (EDFA) gain bandwidth.

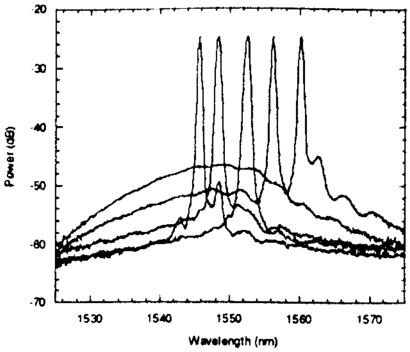
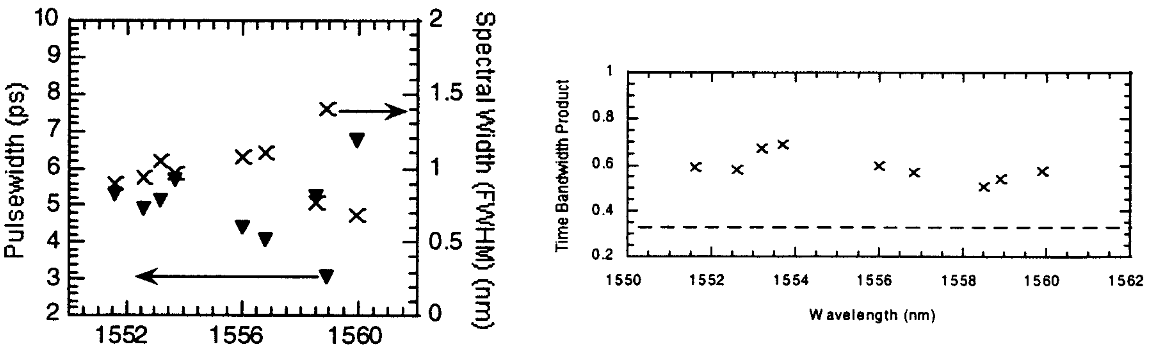


Fig. 5 Optical spectrum of a five element mode-locked laser array designed to be on 400 GHz (3.2 nm) spacing.

Arrays up to 9 adjacent elements have been demonstrated, although the spectrum is not as evenly spaced due to gain pulling effects. While other multi-wavelength soliton transmitters have been demonstrated[8], to the best of our knowledge these are the first multi-wavelength arrays of mode-locked lasers. Tunability of the individual devices over as much as 125 GHz is provided by forward biasing the grating contact (0-15 mA), but is limited by the presence of gain material in the grating region; tuning of the wavelength comb for the entire array of devices can be achieved by temperature tuning. Fig. 6(a,b) shows the pulsewidth, spectral width and the time bandwidth product for all the channels of a 9 element array designed for 200 GHz spacing. The pulsewidth for all the channels is less than 10 ps, limited by the intracavity grating. As seen by us and others[2], similar devices without gratings in the cavity have shown pulsewidths less than 2 ps. The time bandwidth product for these array devices is approximately 1.5-2 times the transform limit, indicating that shorter pulses are possible with external compression[9]. Further optimization of the length and strength of the diffraction grating will allow for more accurate channel spacing and reduction of the spectral bandwidth per channel.



(b)

(a)

Fig. 6 (a) The pulsewidth and spectral width for a nine element mode-locked laser array. (b) The time bandwidth product for the same array. The dashed line indicates the transform limit (0.3148) of the time bandwidth product assuming a sech^2 pulse shape.

4. CONCLUSION

We have demonstrated what we believe to be the largest multi-wavelength array of mode-locked lasers for WDM applications, with up to 9 wavelengths in the EDFA gain bandwidth operating at ~18 GHz on a single chip. All the channels have pulse widths less than 10 ps. The SSB phase noise values are approximately equal to that of the RF clock signal, and the low phase noise and small jitter estimate indicate that the longitudinal modes in the devices are strongly mode-locked. These high performance arrays are potential sources in future soliton-based WDM communication systems.

5. ACKNOWLEDGEMENT

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