

Multichannel Dual-Mode-Based Optical Pulse Source From a Single Laser Diode

H. C. Bao, Y. J. Wen, H. F. Liu, and A. Nirmalathas

Abstract—Generation of multichannel optical pulse trains by spectral slicing of two adjacent optical modes from a single subharmonically synchronous mode-locked laser diode is demonstrated in this letter. The obtained pulse source exhibits high extinction ratio (> 15 dB), low amplitude modulation (< -24.8 dB) and low timing jitter (< 0.5 ps) over all the channels from 1550 to 1564 nm. The resulting pulse trains can be used for the generation of carrier suppressed return-to-zero data in dense wavelength-division-multiplexed systems and optical generation of millimeter-wave signals required for future multiple channel fiber wireless systems.

Index Terms—Carrier suppressed return-to-zero (CSRZ) format, dual-mode, monolithic semiconductor laser, multichannel pulse source, spectral slicing, subharmonically synchronous mode locking, wavelength-division-multiplexed (WDM) systems.

I. INTRODUCTION

WITH THE development of high data rate wavelength-division-multiplexed (WDM) systems, the need for achieving higher spectral efficiency and longer system reach has become the focus of the recent research. The development of advanced modulation formats has been pursued as one of the effective solution to achieve those requirements. Carrier suppressed return-to-zero (CSRZ) is one of such modulation format with advantages such as improved spectral efficiency and reduced intersymbol interference due to the alternating optical phase of successive bits [1]. CSRZ data stream can be generated via synchronous gating of optical pulses with alternating phase using an electrical data stream. A pulse source with alternating phase can be generated using a Mach-Zehnder modulator biased at the null point with a frequency half the bit rate [2] or using mode-locked dual-mode laser diode (LD) [3]. These schemes for CSRZ pulse source generation would suffer high cost for multichannel WDM applications.

Recently, spectral slicing of multiwavelength light from a single laser has become a very attractive technique for providing continuous-wave WDM light source in optical networks because it is not only cost effective but also greatly simplifies wavelength management in the optical network [4]. Since the multiwavelength output of this WDM shared source is determined by a single laser, wavelength alignment to the rest of optical network can be achieved by tracking this single laser. Extracting dual modes from supercontinuum light source is another attractive technique for generating

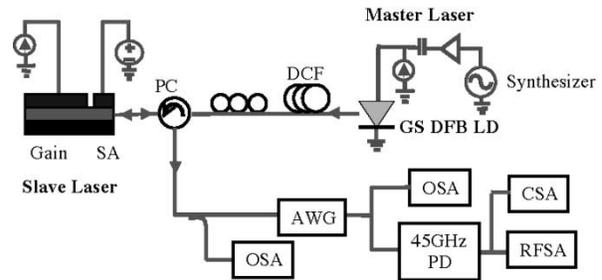


Fig. 1. Experimental setup for generating multichannel dual-mode pulse source.

multichannel dual-mode pulses from a single laser [5]. However, the challenge of this method might be the generation of broad-band supercontinuum light source, involving ultrashort pulse generation, dispersion-flattened supercontinuum fiber, and high-power optical amplifier. In this letter, we proposed a new low-cost technique to generate optical pulse trains from a single LD which can be demultiplexed into a number of pulse trains at different wavelengths with dual-mode optical spectrum and later used for the generation of multichannel 40-Gb/s WDM signals with CSRZ modulation format. This technique is also promising of being used as optical signal generation at microwave or millimeter-wave frequencies in fiber wireless systems, where modulated microwave and millimeter-wave radio signals are transported to and from remote antennas (base station) and central office via an optical fiber. In those applications, the dispersion-induced radio-frequency (RF) power fading is a major limitation for the double side-band format signals generated using an external modulation approach. Using dual-mode optical pulse sources proposed in this letter, RF power fading can be avoided [6] and a cost-effective multichannel WDM source suitable for fiber wireless systems can be developed. Using the proposed method, we have generated 25-channel dual-mode pulse sources with a repetition rate of 32.5 GHz per channel from a subharmonically synchronous mode-locked two-section laser. The performance of the obtained pulse source was also evaluated in terms of extinction ratio, amplitude modulation, and timing jitter.

II. EXPERIMENTAL SETUP

The experimental setup for generating the 32.5-GHz multichannel dual-mode pulse source is shown in Fig. 1. A monolithic semiconductor laser (slave laser) comprised of a gain and a saturable absorber (SA) section with a multimode optical spectrum was used to generate the multichannel optical pulses. The output of laser has a central wavelength around 1560 nm and a mode spacing of 32.5 GHz. When the driving current of the gain section was 159.5 mA and the bias voltage of

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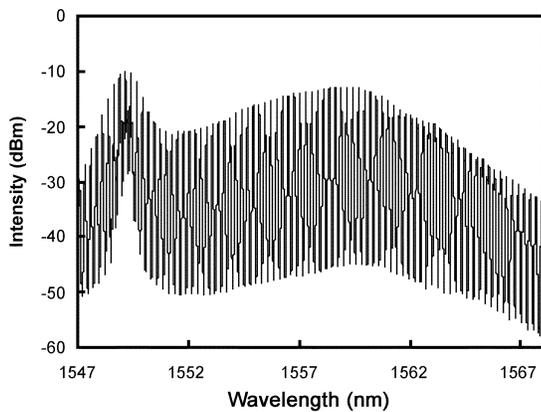


Fig. 2. Optical spectrum of slave laser output before mode slicing.

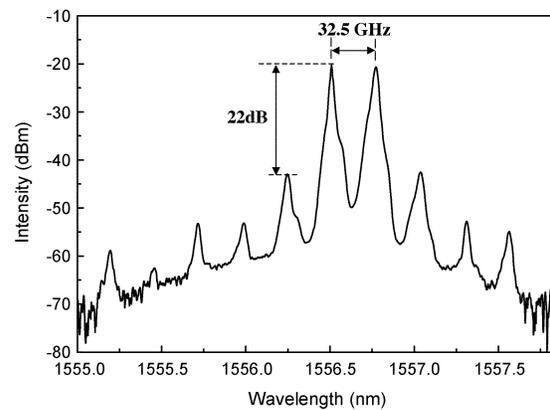


Fig. 3. Optical spectrum of slave laser output after mode slicing at 1556.5 nm.

the SA section was -0.904 V, the laser became passively mode locked and an optical pulse train with a repetition frequency of 32.5 GHz was generated. The passively mode-locked pulses generated from slave laser was stabilized by the injection of an optical pulse train from the master laser, which is a gain-switched distributed feedback (GS-DFB) LD operating at 1550 nm. The pulses with a repetition frequency of 8.125 GHz (one fourth of slave laser resonant frequency) from the DFB LD was compressed by a 1-km-long dispersion compensation fiber ($D = -26.6$ ps/nm/km) before being injected into the slave laser through an optical circulator. The compressed pulses had strong harmonic components, where the fourth-harmonic component provided stable reference for the passive mode-locked (PML) pulses and stabilized the pulses [7]. The slave laser, which is termed as subharmonically synchronous mode-locked LD, was stabilized by the injection of short pulses from GS-DFB LD. Subharmonically synchronous mode locking was used in our scheme since it achieves lower amplitude modulation than subharmonically hybrid mode locking, which stabilizes PML LD via the injection of an electrical signal at a subharmonic of the PML cavity frequency [7]. A four-channel arrayed waveguide grating (AWG) with a channel spacing of 100 GHz and a 3-dB bandwidth of 0.3 nm was used to slice the output of the slave laser and generate multichannel dual-mode pulses with a repetition frequency of 32.5 GHz. The pulses at different wavelength were detected by using an optical spectrum analyzer, a communication signal analyzer, and an RF spectrum analyzer in conjunction with a high-speed photodiode with a bandwidth of 45 GHz.

III. RESULTS AND DISCUSSION

Fig. 2 shows the optical spectrum of the slave laser output before passing through the AWG. The peak around 1550 nm came from the optical injection from the master laser. The broad-band optical modes from 1550 to 1564 nm can be used for the generation of multichannel dual-mode pulses by mode slicing. The power difference of each mode from 1550 to 1564 nm range is less than 10 dB. The wavelength and the intensity of each cavity mode are highly stabilized because the laser is synchronized by the injection of short optical gain-switched pulses [8]. The AWG in the experimental setup (Fig. 1) was used to center at each pair of dual-mode by tuning the temperature and slice out two cavity modes at each channel.

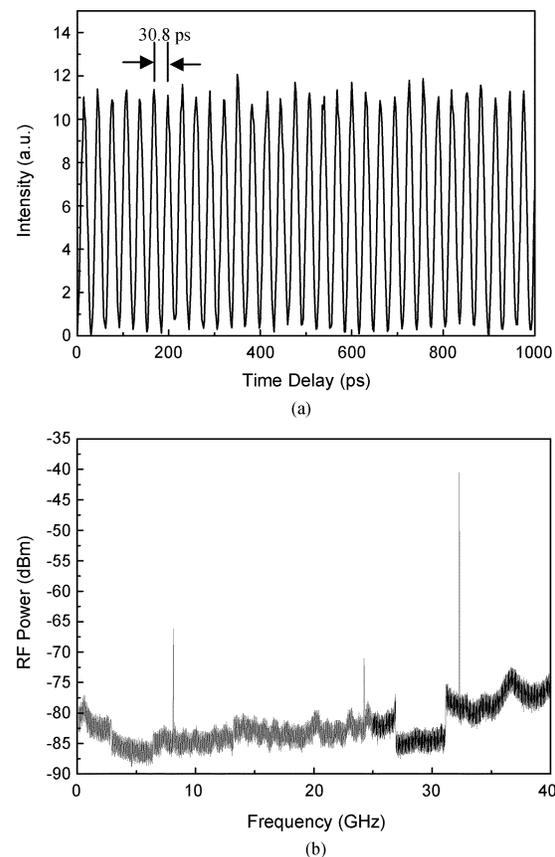


Fig. 4. (a) Time domain waveform of slave laser output after mode slicing at 1556.5 nm. (b) RF spectrum of slave laser output after mode slicing at 1556.5 nm.

Fig. 3 shows the optical spectrum after spectrum slicing at 1556.5 nm, where two cavity modes from slave laser were sliced out and the rejection of adjacent channel was around 22 dB. The separation of two modes is 0.29 nm, corresponding to the cavity resonant frequency 32.5 GHz. The beating of these two modes provides 32.5-GHz pulsed output. Fig. 4(a) shows the time domain waveform of the output confirming the repetition period of pulse train to be 30.8 ps, corresponding 32.5-GHz repetition rate. The extinction ratio of pulses is 17.3 dB. No amplitude modulation was observed from the measured pulses, as shown in Fig. 4(a).

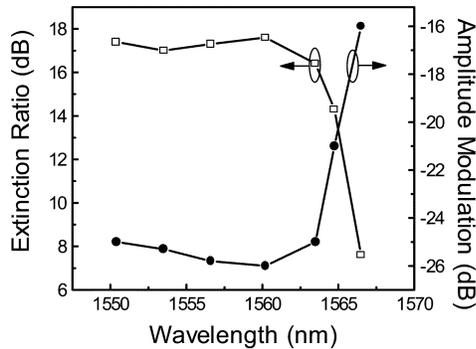


Fig. 5. Extinction ratio and amplitude modulation of generated dual-mode pulses at different wavelengths.

The RF spectrum of the sliced output at 1556.5 nm is shown in Fig. 4(b). The component at 32.5 GHz, which contributes to the oscillation at 32.5 GHz, has large RF power. The RF power of the frequency component at 8.125 GHz, which contributes to the amplitude modulation, is around 25 dB below that of at 32.5 GHz, indicating a very low amplitude modulation in the 32.5-GHz output pulses. A slight increase in relative intensity noise (RIN) at low frequency part is observed due to the inherent aspect of spectrum slicing and we confirmed that the RIN could be suppressed by using a semiconductor optical amplifier [9].

To evaluate the performance of generated multiple-channel dual-mode pulse source, we also measured the extinction ratio, amplitude modulation, and timing jitter at different channels. The measured extinction ratios and amplitude modulation of different wavelengths are shown in Fig. 5. The extinction ratio of the generated dual-mode optical pulses is more than 15 dB for the channels over the range from 1550 to 1564 nm. The extinction ratio of pulses at wavelengths beyond 1564 nm is degraded because the wavelength is at the trailing edge of the slave laser gain profile and the oscillation at these wavelengths starts to be suppressed. The amplitude modulation which is the ratio of the RF power at the injection frequency (8.125 GHz) to that at the slave laser cavity resonance frequency (32.5 GHz) was calculated based on the measured RF spectrum of the output after mode slicing. The amplitude modulation is below -24.8 dB for all channels from 1550 to 1564 nm. This low amplitude modulation can be attributed to the low injection power (-5.17 dBm) required for stabilizing slave laser.

Fig. 6 shows the measured phase noise at 10-kHz offset and timing jitter of the pulses at different wavelength. The phase noise of the generated pulses is under -90 dBc/Hz for all the wavelength evaluated. This low level of phase noise can be attributed to the good mode-locking of the multiple wavelength slave laser and the low phase noise of the synthesizer. The timing jitter was calculated by integrating the measured single-sideband noise (from 100 Hz to 10 MHz) at the detected signal component corresponding to the repetition rate of the pulses (32.5 GHz). The timing jitter of the generated dual-mode pulses is below 0.5 ps for all channels from 1550 to 1564 nm.

IV. CONCLUSION

We have demonstrated a novel technique for the generation of wide-band dual-mode pulse source from a single subharmoni-

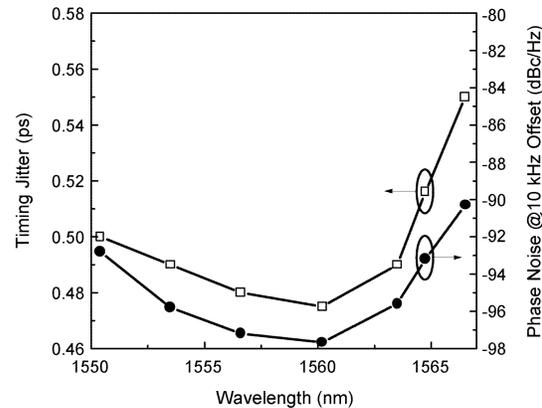


Fig. 6. Phase noise at 10-kHz offset and timing jitter of generated dual-mode pulses at different wavelengths.

cally synchronous mode-locked LD. The obtained pulse source exhibits high extinction ratio (>15 dB), low amplitude modulation (<-24.8 dB), and low timing jitter (<0.5 ps) over all the channels from 1550 to 1564 nm. The proposed technique is cost-effective, and the generated pulse train is a promising candidate as pulse source for the generation of CSRZ data in dense WDM systems and optical signal source at millimeter-wave frequencies in multiple channel fiber wireless systems.

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