Multirate and Dual-Wavelength Semiconductor Fiber Laser

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***Abstract*—We demonstrate the successful operation of a multirate and dual-wavelength mode-locked semiconductor fiber laser that incorporates a multichannel nonlinear optical loop mirror (NOLM) functioning as a multichannel all-optical modulator. Each channel of the NOLM incorporates its own length of highly nonlinear fiber and can be driven by independent pump signals. Thus, the single NOLM is capable of processing multiple wavelength channels independently and simultaneously. We obtain mode-locked operation at different frequencies (5 and 10 GHz) for two wavelengths with spacing as narrow as 0.8 nm.**

***Index Terms*—Nonlinear optics, optical fiber devices, pulsed lasers, semiconductor optical amplifiers (SOAs).**

I. Introduction

MULTIWAVELENGTH and short pulse laser sources are of interest for optical signal processing and high-speed optical communications systems. Although optoelectronic devices show a gradual improvement in performance as the technology matures, all-optical processes are still desirable as they provide the potential for ultrahigh-speed switching and processing applications. The advent of various types of specialty optical fibers has attracted considerable interest for all-optical processing functions and all-optical switching based on nonlinear effects. Devices such as nonlinear optical loop mirrors (NOLMs) have been widely used for performing ultrafast all-optical processing functions and as all-optical modulators to mode-lock fiber lasers [1]–[3]. The availability of fibers with enhanced nonlinearities has opened new possibilities for designing all-optical modulators based on NOLMs. In particular, silica-based highly nonlinear fibers (HNLFs) are compatible with standard single-mode fibers and their dispersive properties can be easily tailored [4]. Thus, HNLFs offer a simple way of enhancing the performance of all-optical NOLM modulators.

Simultaneous mode-locking of two laser cavities at two different wavelengths using a single NOLM has been demonstrated [5]. However, increased flexibility can be achieved by increasing the number of laser cavities in the NOLM. This work is inspired by the recent proposal of the arrayed waveguide Sagnac interferometer (AWSI) [6]. Since several independent and wavelength-selective fiber loops are available within the AWSI, this arrangement offers the possibility of incorporating nonlinear elements for each channel, thereby giving the potential to perform multichannel optically triggered modulation. Thus, the AWSI is a single and simple device that can be used to implement N parallel NOLMs, each operating at a different wavelength and therefore capable of processing multiple wavelength channels independently and simultaneously. In this work, we demonstrate a dual-wavelength mode-locked semiconductor fiber laser (SFL) using a multichannel NOLM as a multichannel optical modulator. The NOLM is based on an AWSI, and the individual laser wavelengths can be mode-locked independently by different optical pump signals. Semiconductor optical amplifiers (SOAs) are used in this configuration to allow for dual-wavelength operation and HNLFs are incorporated in each channel within the NOLM. We investigate the performance of the SFL operating with different channel spacing and for diverse pumping conditions.

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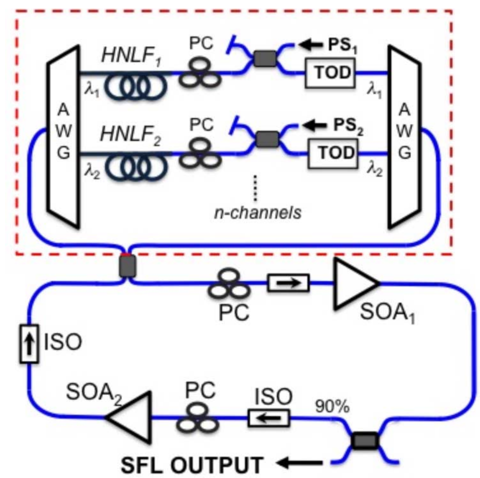

Fig. 1. Experimental setup: the dotted box encloses the multichannel NOLM (ISO: isolator; PC: polarization controller; TOD: tunable optical delay).

II. Experiments

The experimental setup is shown in Fig. 1. The laser cavity comprises two SOAs for gain; the multichannel NOLM is based on two arrayed waveguide gratings (AWGs) with 100-GHz channel spacing [6]. The 3-dB channel bandwidth is 0.2 nm and the insertion loss is 5 dB. The interconnected channels also include a length of HNLF, a polarization controller, a

TABLE I
SPECIFICATIONS OF THE HNLFs USED IN THE NOLM: LENGTH (L), LOSS (α), NONLINEAR COEFFICIENT (γ), AND DISPERSION SLOPE (S)

	L [m]	α [dB]	γ [W^{-1}·km^{-1}]	S [ps/(nm^2·km)]
$HNLF_1$	980	1.17	11.5	0.02
$HNLF_2$	1007	1.43	11.5	0.01

tunable optical delay, and a 3-dB coupler to inject the pump signal. In our experiments, we modulate only two channels due to component availability. Each channel of the NOLM can be switched independently via cross-phase modulation and mode-locking operation at each of the two wavelengths can be achieved for different pump signals. Note that the filtering nature of the AWG removes the pump signals from the output. The specifications of the two HNLF spools used in our experiments are shown in Table I.

Two independent laser sources are used for the pump signals. Pump signal 1 (PS1) is a commercial wavelength-tunable pulsed source (5 ps), and pump signal 2 (PS2) is obtained by modulating a narrow linewidth tunable laser source with an electrooptical modulator. We use separate frequency synthesizers so that there is no phase synchronization between the pump signals. Moreover, pump parameters such as modulation frequency and wavelength can be adjusted independently. An additional 3-dB coupler (not shown) is used at the output of the fiber laser. One arm of the coupler is connected to an optical spectrum analyzer (0.06-nm resolution) and the remaining arm is used for observing the signal in the time domain. This signal is amplified by an erbium-doped fiber amplifier and monitored either with a digital oscilloscope and an optical sampling module with an impulse response time of 16 ps or an autocorrelator. The individual temporal waveforms (i.e., at each wavelength) are measured after filtering the amplified output wavelength using a tunable bandpass filter with a 0.8-nm spectral bandwidth.

III. RESULTS

We begin by mode-locking the SFL at two wavelengths using separate pumps at a frequency of 10 GHz. The performance of the mode-locked SFL is evaluated by considering the output pulse characteristics, such as pulse width, time-bandwidth product ($\Delta\tau \cdot \Delta\nu$), peak-to-peak amplitude variations, and root-mean-square timing jitter ($\sigma_{\rm rms}$) measured using the sampling oscilloscope running in persistence mode (200-ms persistence time). These latter two measurements were obtained at each wavelength for single and dual-channel operation. λ_1 was pumped with PS_1 operating at $\lambda_{\rm p1} = 1560$ nm with an average power of 40 mW and $\sigma_{\rm rms} = 0.86$ ps; λ_2 was pumped with PS_2 operating at $\lambda_{\rm p2} = 1565$ nm with an average power of 70 mW, 40% duty cycle, and $\sigma_{\rm rms} = 2.17$ ps. The difference in pump powers required for each channel is due in part to the different duty cycles of the pump signals.

The output pulse characteristics were measured for different wavelength spacing ($\Delta\lambda = |\lambda_1 - \lambda_2|$). Fig. 2 shows the SFL output spectrum and individually filtered pulses in the time domain when both channels were mode-locked simultaneously with $\Delta\lambda = 2.4$ nm ($\lambda_1 = 1551.5$ nm, $\lambda_2 = 1553.9$ nm). The corresponding output spectrum and pulses when $\Delta\lambda = 0.8$ nm ($\lambda_1 = 1551.5$ nm, $\lambda_2 = 1550.7$ nm) are shown in Fig. 3.

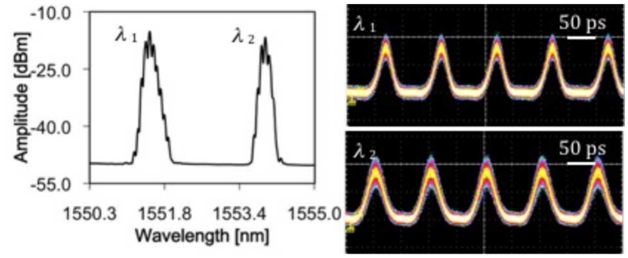

Fig. 2. SFL output spectra and pulses for dual wavelength operation (wavelength spacing: 2.4 nm).

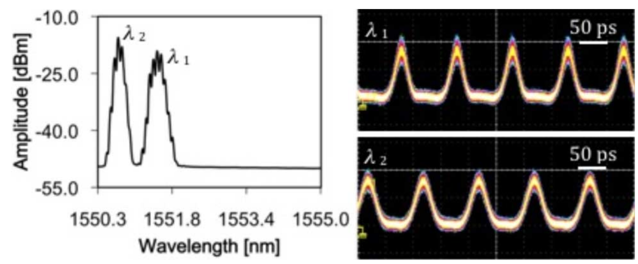

Fig. 3. SFL output spectra and pulses for dual-wavelength operation (wavelength spacing: 0.8 nm).

TABLE II
MODE-LOCKED FEATURES FOR DIFFERENT WAVELENGTH SPACING ($\Delta\lambda$)

	$\Delta\lambda$ = 2.4 nm					
	Single Channel			Dual-Channel		
	$\Delta\tau$ [ps]	$\Delta\tau\cdot\Delta\nu$	σ_{RMS} [ps]	$\Delta\tau$ [ps]	$\Delta\tau\cdot\Delta\nu$	σ_{RMS} [ps]
λ_1	20.47	0.41	1.33	22.90	0.46	2.20
λ_2	25.34	0.49	2.06	29.40	0.56	3.10
	$\Delta\lambda$ = 0.8 nm					
	Single Channel			Dual-Channel		
	$\Delta\tau$ [ps]	$\Delta\tau\cdot\Delta\nu$	σ_{RMS} [ps]	$\Delta\tau$ [ps]	$\Delta\tau\cdot\Delta\nu$	σ_{RMS} [ps]
λ_1	18.21	0.36	1.27	19.23	0.38	2.34
λ_2	26.02	0.49	1.92	28.28	0.54	2.05

The SFL output features for both cases are summarized in Table II. Regardless of the wavelength spacing, simultaneous mode-locking at two wavelengths yields similar pulse characteristics to those obtained for single-channel operation. Nevertheless, some crosstalk is evident: the peak-to-peak amplitude variations increase from 15% for single-channel operation to 25% for dual-channel operation. Similarly, there is an increase in $\sigma_{\rm rms}$ for dual-channel operation. Notice that in principle, shorter pulses can be obtained using an AWG with a broader channel bandwidth. Pulse shortening/shaping can also occur through nonlinear interaction within the NOLM; for instance, soliton-like pulses are obtained with the anomalous dispersion of $HNLF_1$ for λ_1.

Next, we further examined the performance of the SFL for different spacing between the pump and signal wavelengths. This was done either by tuning the wavelengths of the pump lasers or by changing the operating channels of the AWSI (i.e., changing the lasing wavelengths). Pump and signal wavelength separations as large as 20 nm were tested and in all cases, the pulse characteristics were again very similar to those reported in Table II. This is due to the flattened and low dispersion of the HNLFs, which yields a short switching window despite a

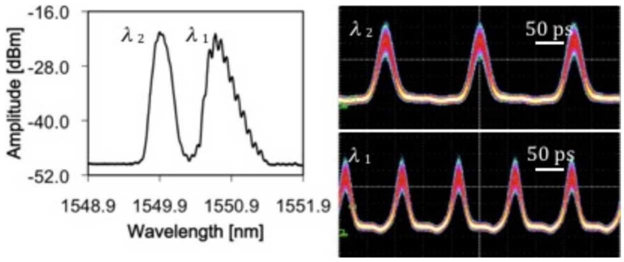

Fig. 4. SFL output spectra and pulses for dual-wavelength operation at two different frequencies.

TABLE III
MODE-LOCKED FEATURES FOR MULTIRATE OPERATION

	Single Channel			Dual-Channel		
	$\Delta\tau$ [ps]	$\Delta\tau\cdot\Delta\nu$	σ_{RMS} [ps]	$\Delta\tau$ [ps]	$\Delta\tau\cdot\Delta\nu$	σ_{RMS} [ps]
λ_1	14.1	0.45	1.42	13.7	0.47	2.43
λ_2	19.5	0.53	2.18	20.8	0.57	2.85

large wavelength separation between the pump and laser signals [7]. Thus, our proposed configuration offers remarkable flexibility for choosing the wavelengths of the pump signals, and each wavelength can be mode-locked independently.

Finally, we demonstrate multirate operation, i.e., when two wavelengths are mode-locked at different frequencies. Fig. 4 shows the output spectra and pulses for $\Delta\lambda = 0.8$ nm. λ_2 (1549.9 nm) is mode-locked at 5 GHz using PS2 operating at $\lambda_{\rm p2} = 1557$ nm with an average power of 75 mW and $\sigma_{\rm rms} = 2.24$ ps. λ_1 (1550.7 nm) is mode-locked at 10 GHz using PS1 operating at $\lambda_{\rm p1} = 1540$ nm with an average power of 40 mW and $\sigma_{\rm rms} = 0.95$ ps. The pulse features for single- and dual-channel operation are shown in Table III. Again, simultaneous mode-locked operation at two different frequencies does not affect significantly the pulse features obtained for single channel operation (though as before, crosstalk is observed since the peak-to-peak amplitude variations increase from 18% to 28% for single- and dual-channel operation, respectively, and $\sigma_{\rm rms}$ also increases). Although only two different modulation frequencies were tested, we do not foresee limitations for using other frequencies. Thus, multirate and dual-wavelength operation can be attained with the proposed configuration.

IV. Discussion and Summary

The multichannel NOLM modulator offers outstanding flexibility for achieving simultaneous mode-locking operation at different wavelengths. As seen in our experiments, each loop within the NOLM can be adjusted individually, thus, each wavelength can be modulated with independent pump signals at different frequencies. For a given number of channels in the modulator, the number of wavelengths available will be ultimately limited by the gain medium used for the laser. In particular, as the number of wavelengths increases, some crosstalk due to cross-gain modulation and and cross-phase modulation effects should be expected. These are evident by the increase in peak-to-peak amplitude variations and $\sigma_{\rm rms}$. Thus, the influence of crosstalk has to be considered in order to estimate the maximum number of wavelengths attainable with this configuration. In our case, with SOAs, we were able to obtain dual-wavelength operation, even for a wavelength separation as narrow as 0.8 nm and at two different modulation frequencies. Thus, our proposed configuration performs well for multirate dual-wavelength mode-locked operation.

The multichannel NOLM modulator allows for direct modulation on each channel independently with modulation frequencies limited only by the nonlinear response of the fiber. Notice that the modulator is optically triggered and optical processing functions such as clock recovery might benefit from a multi-wavelength laser actively mode-locked by optical signals [8]. Furthermore, other types of nonlinear media or devices (e.g., PCFs, chalcogenide fibers, electroabsorption modules) can be incorporated in each channel. Thus, this configuration should allow the performance of different optical processing functions simultaneously on different channels.

In summary, we have demonstrated a dual-wavelength mode-locked SFL based on a multichannel NOLM. Modulation of each wavelength is achieved through cross-phase modulation owing to the use of HNLFs on each modulator channel. The proposed configuration allows for multirate mode-locking operation using a single device capable of processing multiple wavelength channels simultaneously and independently. The possibility of accessing each channel individually makes this configuration a versatile and flexible approach for realizing all-optical parallel processing.

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