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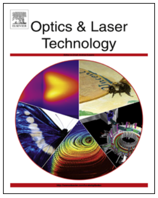

Tunable multiwavelength mode-locked fiber laser using intra-cavity polarization and wavelength dependent loss

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ABSTRACT

We report a tunable multiwavelength mode-locked fiber ring laser in C-band. Multiwavelength characteristic and tuning of laser wavelengths is achieved by inducing polarization and wavelength dependent loss in the cavity by using a combination of two polarization controllers (PCs) and an intensity modulator, inserted between the two PCs. With this technique we obtained pulses of 14 ps (FWHM) at a repetition rate of 10 GHz by actively mode-locking the laser. We obtained simultaneous lasing of 5 wavelengths with 3-dB spectral width of 0.2 nm for each lasing wavelength. We measured short-term stability of the pulses and corresponding spectra by continuously collecting time and spectral domain data for 600 s, sampled at an interval of 20 s. The pulsewidth was measured to be stable to within ± 732 fs and peak power fluctuations were within ± 0.16 mW. For simultaneous lasing of two wavelengths, the linewidth was found to be stable within ± 0.07 nm with a peak power fluctuation of ± 1 dB.

1. Introduction

Tunable multiwavelength pulsed lasers are used in several applications such as dense wavelength division multiplexed (DWDM) optical communication systems, optical fiber sensors, optical clocks, spectroscopy, optical instrument testing and characterization, etc. [1–3]. In addition to the multiwavelength characteristic, simple structure, low cost, exhibition of low noise behavior, narrow linewidths and tunability over a wide range are some of the characteristics of these lasers that are important in above applications [4–6].

Many techniques such as loss modulation, intra-cavity filters and intra-cavity birefringence have been investigated for achieving tunability and multiwavelength operation in erbium (Er^{3+}) doped fiber lasers in C-band. Implementation of these techniques using semiconductor optical amplifiers (SOAs), optical filters, fiber Bragg gratings (FBGs), and intra-cavity birefringence comb filter can be found in literature [7–12]. However, the lasers implemented using these techniques provide limited tuning range. For broader tuning range and stable operation, techniques based on nonlinearities are used. In [13], four-wave mixing (FWM) was used to generate stable multiwavelength comb. However, generation of FWM required pump power of 160 mW and an additional FBG was required for simultaneous multiwavelength lasing of upto five wavelengths. In [14], the laser was passively mode locked using nonlinear polarization rotation (NPR) technique. The pump power used in the experiment was around 75 mW. Also, due to passive mode locking, the half-power spectral bandwidth was greater than 0.80 nm. In [15] also, NPR technique was utilized to suppress supermode noise. A tuning range of approximately 12 nm with full width half maximum (FWHM) pulsewidth of 23 ps was obtained at a pump power of 300 mW. These techniques provide broader tuning range at the expense of requiring high pump powers and increased hardware complexity.

In this paper, we describe a technique to obtain broad range tunability and multiwavelength operation of an Er^{3+} doped fiber ring laser. Our technique is based on inducing polarization and wavelength dependent loss in the laser cavity. Two polarization controllers (PCs) that can change the state of polarization (SOP) of the light continuously and a $LiNbO_3$ Mach-Zehnder intensity modulator (MZIM) inserted between the two PCs, rotate the SOP of light inside the cavity, inducing polarization dependent cavity loss which also varies with wavelength of light. This polarization and wavelength dependent loss (PWDL) allows selection as well as tuning of the lasing wavelengths. Using PWDL, the central wavelength of our laser can be tuned over the wavelength range {1530–1562 nm} with a tuning range of ≈ 32 nm.

The laser was actively mode locked using intensity modulator at a repetition rate of 10 GHz and stable pulses with pulsewidth as low as 14 ps and spectral width ≈ 0.2 nm were obtained. The frequency of the RF signal and pump current were continuously tuned using a control algorithm after interfacing the laser setup to

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MATLAB [16]. The pulsewidth was found to be stable to within ≈732 fs and power fluctuations within ≈0.16 mW. Also, the wavelength drift for two simultaneous wavelengths was found to be ±0.07 nm with peak power deviation of ±1 dB over a time interval of 600 seconds.

The organization of this paper is as follows. Section 2 describes PWDL and its experimental realization. The schematic of our mode locked laser is described in Section 3. In Section 4, results of the fiber laser experiment are reported. We conclude by summarizing results in Section 5.

2. Principle of PWDL

In this section we describe the principle behind polarization and wavelength dependent loss (PWDL) used to implement tunable, multiwavelength fiber laser and characterize it experimentally. PWDL can be obtained by placing a birefringent material between two PCs. The PCs consist of 3 plates in QWP-HWP-QWP configuration and provide endless SOP control [17]. The PCs utilize stress-induced birefringence to alter the polarization of the incoming light. The retardation caused by the PC plates due to the induced birefringence is a function of wavelength of light. By rotating the plates, the arbitrary polarization can be converted to linearly polarized light or rotate the linearly polarized light.

Fig. 1 shows the mechanism of PWDL. The first PC changes the SOP of incoming light and converts the arbitrary polarized light to linearly polarized light. A $LiNbO_3$ MZIM introduces birefringence between two polarization components of light beam. The birefringence induced by the modulator depends on the wavelength via half-wave voltage $V_\pi = \lambda d / n_e^3 r_{33} l$ [18]. The induced birefringence is converted to phase shift between propagating eigenmodes, the phase-shift being proportional to applied voltage to the modulator. Thus, MZIM rotates the SOP of light inside the cavity. The second PC may further be adjusted to rotate the linearly polarized light and selectively transmit the light. By changing the amplitude of the voltage applied to MZIM and wavelength of light, SOP can be changed at the output of the second PC. Thus, the combination of MZIM and two PCs induces polarization dependent loss (PDL) in the cavity which varies with wavelength.

We used the setup in Fig. 2 to characterize the PWDL. A tunable laser module (Agilent N7714A) was used as light source and the output optical power was measured by an optical power meter. An MZIM (Covega LN56S) was placed between two PCs to obtain PWDL.

The birefringence induced by the modulator depends on the polarization change induced by PC1. We study the effect of induced birefringence on the cavity loss by varying the angles (θ_1) of PC1 plates while keeping PC2 plates at a reference angle of $\theta_2 = 0°$. In this experiment, loss is defined as the ratio P_{out}/P_{ref}, where, P_{ref} is the optical power measured at $\theta_1 = \theta_2 = 0°$ and P_{out} is the output power for different values of θ_1.

Fig. 3a shows the measured loss as a function of wavelength with and without modulation voltage. Plate1 of PC1 was set to 60° in the clockwise direction with the other two plates set at 0°. All the angles were measured from zenith. By applying the modulation voltage, we observe shift in cavity loss with respect to wavelength, thus demonstrating the dependency of birefringence on modulation voltage. By varying the amplitude of applied voltage, laser wavelengths can be tuned.

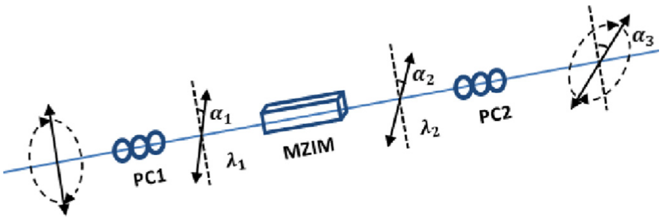

Fig. 1. Schematic diagram to show the principle of PWDL.

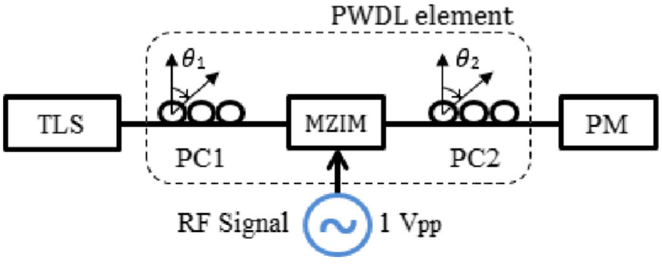

Fig. 2. Schematic diagram of the experimental setup to measure PWDL. TLS: Tunable laser source, PC: Polarization controller, MZIM: Mach-Zehnder intensity modulator, PM: Power meter.

Fig. 3b shows the measured loss as a function of plate angle of PC1 at $\lambda = 1550$ nm. The loss curves are shown by varying the angle of each of the three paddles of PC1 individually while keeping the other two paddles at 0°. Fig. 3c shows the measured loss as a function of wavelength. The angle of one paddle of PC1 was fixed at −60° respectively while keeping two paddles set at 0°. Similarly, in Fig. 3d loss is shown as a function of wavelength for plate1 of PC1 at different angles. From the four tuning curves of Fig. 3, we notice dips in optical power at certain wavelengths and PC angles. When this setup is inserted in the ring laser cavity, shown in Fig. 4, the wavelengths with lower losses lase readily compared to the wavelengths with higher losses. Thus, we obtain multiwavelength lasing. Since the loss is a function of wavelength as well, the setup provides tunability of the laser.

3. Experimental setup

Fig. 4 shows the experimental setup of our Er^{3+} doped fiber ring laser (EDFRL). The laser cavity consisted of an EDF (Optiwave AMP901) of approximate length 30 m, acting as the active element and was driven into saturation by a 980 nm pump laser diode. It was followed by an isolator and a $LiNbO_3$ MZIM (Covega LN56S) placed between two PCs. The combination of PCs and MZIM acts as PWDL element as described in Section, 2. The MZIM has V_π of 7 V_{pp} at 1550 nm. The modulator was driven by an RF signal of frequency 10 GHz and an amplitude of 1 V_{pp}. A 3 dB fiber coupler was used to draw a portion of optical signal out of the cavity and feed the remaining back to the cavity. A high speed sampling oscilloscope (Agilent Infiniuum DCA-X86100D) was used to monitor the mode locked laser (MLL) pulses and measure their temporal characteristics while the spectrum of the MLL was measured using optical spectrum analyzer (Agilent 86142B).

The total cavity length was approximately 39 m, giving a fundamental repetition rate of 5.02 MHz. We modulated the cavity loss at 10 GHz which corresponds to 1992nd harmonic of the fundamental. Due to the absence of an optical filter in the cavity, lasing wavelength of the MLL was determined by cavity losses which in turn was determined by PC angle and modulation voltage as described in Section, 2. The wavelength with smaller loss lases readily compared to the wavelength with higher relative loss.

The setup was interfaced to MATLAB. A control algorithm tuned the frequency of the RF signal and pump current to stabilize pulses as well as to facilitate self-starting operation of the laser. In the control algorithm, the data from the oscilloscope was fit to $\text{sech}^2(.)$ function: $I = I_0 \, \text{sech}^2[\alpha(t - T_0)]$ iteratively. Here I_0, α and T_0 are the variables controlling the parameters viz. intensity, pulsewidth and