Optical Frequency Sweeper Using an Optical Ring Circuit with a Tunable Injection-Locking Filter

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***Abstract*—We report an optical-frequency sweeper based on an optical ring circuit containing an optical-frequency shifter and a delay-line fiber. High signal-to-noise ratio (30 dB) is achieved by introducing a tunable injection-locking filter (TILF). The TILF utilizes a tunable laser (distributed Bragg reflector (DBR) laser), which is injection locked to an input signal light. We have achieved a total sweep frequency of 144 GHz by switching the longitudinal modes of the DBR laser.**

***Index Terms*—Optical frequency conversion, optical frequency synthesizers, injection locking, light sources.**

I. INTRODUCTION

ABSOLUTE optical frequency synthesis will increase in importance as a means of producing arbitrary optical frequency references for future photonic networks. In the photonic networks, the number of optical channels has to be increased to increase the transmission capacity of wavelength-division-multiplexing (WDM) systems by narrowing of WDM channel spacing. Therefore, for constructing systems with frequency accuracy, precise optical frequency control of signal sources is indispensable using highly stabilized optical-frequency references and optical-frequency test equipment with high resolution and accuracy. The optical frequency synthesizer is one of the promising candidates for the frequency reference and test equipment. For future high capacity WDM systems, it must have wide tunability covering WDM channels, a high signal-to-noise ratio (SNR), and high resolution (for test equipment use) in addition to frequency accuracy. Optical-frequency sweepers using an optical ring circuit have been used for absolute frequency synthesis [1]–[3]. These sweepers synthesize many optical frequencies by successive frequency shifting of the seed light. This method has the potential to provide a wide sweep frequency range with accuracy. The frequency accuracy of the output light is determined by the accuracy of the frequency shifter used for frequency shift and the seed light. Because the frequency shifter has an accuracy of better than 10^{-6}, the output light's frequency also have accuracy when only one highly stabilized light source is employed as a seed light. The optical ring circuit contains an optical frequency shifter and an optical delay line. The conventional optical ring circuit also employs an optical amplifier for loop loss compensation. A pulsed seed light, whose pulsewidth is set at the round-trip time of the ring or narrower, is launched into the optical ring and circulates in it. The pulsed light undergoes a frequency shift with each circulation. Thus, the ring generates an optical-pulse train with a constant increment (or decrement) frequency and an interval time. Therefore, a pulse with an arbitrary optical frequency can be obtained by selecting the time-slot.

While this method can generate an arbitrary optical frequency accurately, problems may occur due to the amplified spontaneous emission (ASE) noise that is generated from the optical amplifier and accumulates with the number of circulations. The accumulated noise degrades the SNR of the output light and limits the total sweep frequency range, which is proportional to the number of circulations. Tunable bandpass filters can suppress the noise and increase the total sweep frequency [3]. However, the SNR remains low. In this letter, we propose an optical-frequency sweeper that is free from the noise-accumulation problem, thereby achieving a higher SNR output. The sweeper employs a narrow-band filter utilizing injection locking in a tunable laser, so we call it a tunable injection-locking filter (TILF). The tunable laser in the lasing state can be used as a very narrow pass band (∼ laser-line width) filter with constant output optical power, constant polarization capability, and optical-frequency tunability when it is injection locked to an input light. As a result, an optical amplifier is not needed in the optical ring circuit.

II. EXPERIMENT

The experimental configuration of an optical ring with our TILF is shown in Fig. 1. The TILF consists of a three-electrode distributed Bragg reflector (DBR) laser and an optical circulator. The optical ring contains a fiber-pigtailed acoustooptic frequency shifter (AOFS), whose shift frequency is -120 MHz, and a 1-km-long standard single-mode fiber as an optical delay line. The master laser is highly stabilized to 193.4000 THz, which is coincident with one of the grid frequencies in the ITU-T recommendations [4], using offset locking on an acetylene ($^{13}C_2H_2$) gas-absorption line with the accuracy of ±50 MHz [5]. A seed pulse is generated by the CW master laser and the electrooptic modulator (EOM), launched into the optical ring through the optical-fiber coupler, and then introduced into the AOFS. The first-order output of the AOFS (with frequency shift) is sent to the TILF and the zeroth-order output of the AOFS (without frequency shift) is used to monitor the time- and spectral-resolved output-light-power profile by using the Fabry–Perot etalon. The regenerated light from the TILF leads to the delay line. The polarization

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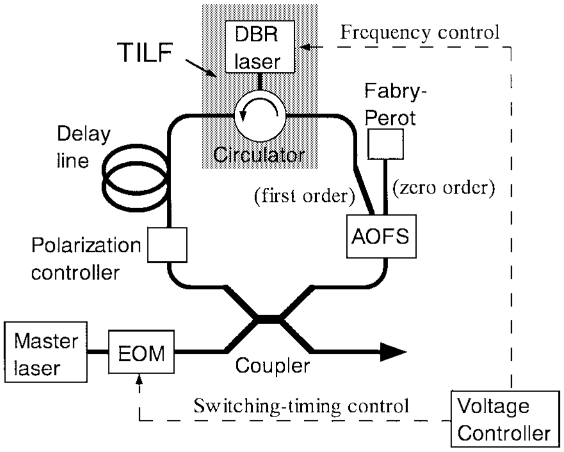


Fig. 1. Schematic of the optical sweeper using an optical ring circuit with a TILF. EOM: Electrooptic modulator. AOFS: Acoustooptic frequency shifter. DBR laser: Distributed Bragg reflector laser.

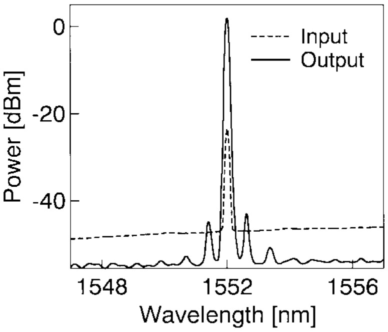


Fig. 2. Filtering characteristics of the TILF. The dashed line shows input light, which consists of distributed feedback laser light and amplified spontaneous emission noise from an EDFA. The solid line shows the output light of the TILF.

controller adjusts the signal polarization so that the TILF can be best performing. The optical ring has a loop loss of $\sim$16.4 dB, excluding the TILF loss, and a round-trip time of $\sim$5.1 μs. The pulsewidth of the launched master light is set to $\sim$3 μs in this experiment so that the injection-locking and free-running condition can be differentiated by monitoring the frequency change. The free running part (unlocked part) of the output, of course, can be eliminated for practical use by setting the pulsewidth of the master light to the round-trip time.

The frequency control of the DBR laser and the switching-timing control of the EOM are done by the programmable voltage controller. The optical frequency of the DBR laser is controlled through the DBR and the phase-controller electrodes. The optical frequency map plotted against voltages to the DBR and the phase-controller electrodes was utilized for creating a series of voltage data given to the controller. The series was designed so that the free-running frequency of the laser changed every six round-trips by −720 MHz (−120 MHz × 6). The frequency deviation between the free-running and the circulating signal light had to be maintained within the locking range to activate the TILF. The filtering characteristics of our TILF are shown in Fig. 2. The currents of the phase controller and DBR region are set to be locked to the input signal light. The input light (dashed line) consisted of

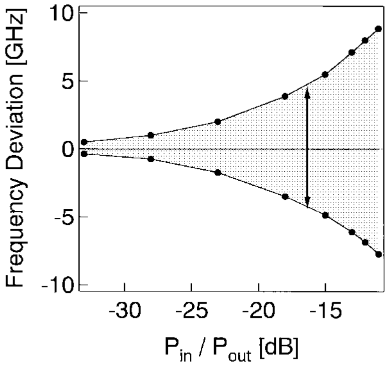
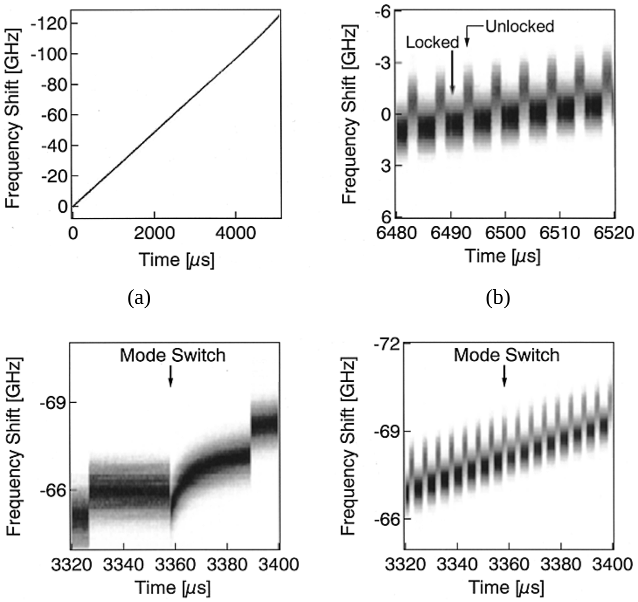


Fig. 3. Allowable frequency deviation of the TILF versus $(P_{\rm in}/P_{\rm out})$. The vertical axis shows the frequency deviation of the input light from the free-running frequency. The shaded area shows the injection-locking range or active range of the TILF. The arrow indicates the allowable frequency deviation at the loop loss of the optical ring (16.4 dB).

a distributed feedback (DFB) laser light as signal (−23 dBm) and ASE noise (peak power of −46 dBm) from a fiber amplifier. The output light of the TILF (shown as a solid line) undergoes 25-dB regeneration in signal light and 7-dB suppression in noise light. Thus, the TILF improves the SNR, although the noise suppression was limited by the sidemode-suppression ratio of the DBR laser. The allowable frequency deviation of the TILF is shown in Fig. 3 as a function of the input-to-output power ratio $(P_{\rm in}/P_{\rm out})$ of the TILF. The vertical axis shows the frequency deviation that is the input light frequency subtracted by the free-running frequency of the TILF. The free-running frequency was fixed at 193.4 THz. The locking range (shaded area) becomes wider as $P_{\rm in}/P_{\rm out}$ increases in this power-ratio range. The locking range of the DBR laser in the optical ring is estimated at −4.5 to 4.1 GHz from the loop loss of the optical ring (16.4 dB, excluding the TILF), as indicated in Fig. 3 by the arrow. Then, the required frequency control accuracy of the TILF is $\sim\ \pm$4 GHz.

A synthesized light pulse-train is successfully created by launching a seed pulse into the optical ring. The time- and spectral-resolved power profiles of the output light are shown in Fig. 4. The optical frequency shifted on a line with a slope of −120 MHz/circulation as shown in Fig. 4(a). Magnified successively injection-locked pulse-trains are shown in Fig. 4(b). Owing to seed pulsewidth being narrower than the round-trip time, injection-locked and -unlocked frequencies appear alternately, which reveals successive injection locking.

In three-electrode DBR lasers, longitudinal mode switching is needed to access full quasicontinuously tuning range as wide as 800 GHz. To minimize thermal drift and output power change, the mode switching has to be introduced every longitudinal-mode spacing of the DBR laser (100 GHz, for the TILF). At $t = 3360$ μs, the voltage applied to the phase-controller region was changed abruptly to introduce a phase shift. A mode switching to the neighbor mode was realized without an optical frequency change. Quasicontinuous frequency sweep under free-running conditions was achieved as shown in Fig. 4(c). After the mode switching, frequency chirping appears, which is the thermal effect caused by the rapid change of control voltage. However, the free-running



(a) (b)

(c) (d)

Fig. 4. Power profiles of the output light from the sweeper as a function of time and frequency shift. (a) A wide range. (b) A narrow range around $t = 6500\ \mu$s. (c) Under free-running condition and (d) injection-locked condition around a mode-switching point ($t = 3360\ \mu$s).

frequency kept the allowable frequency deviation. By introducing a seed pulse, the DBR laser was continuously injection locked to the feedback light even at the mode-switching point introduced at $t = 3360\ \mu$s as shown in Fig. 4(d).

Successive injection locking continued up to $t = 6500\,\mu$s as shown in Fig. 4(b). The number of circulations and total sweep frequency were thus estimated to be 1200 and 144 GHz, respectively. The SNR of the output light was estimated to be over 30 dB.

In this experiment, the total sweep frequency was limited to 144 GHz due to insufficient accuracy of the TILF control. The frequency deviation between the free-running TILF and the circulating light exceeded the allowable range (∼ ±4 GHz) and the successive injection locking was not obtained over a 144-GHz range. By optimizing the TILF control, the sweeper will be able to cover the whole tuning range of the DBR laser or the TILF (∼800 GHz).

III. CONCLUSION

We have developed an optical-frequency sweeper with a bandpass filter using injection locking in a DBR laser for high SNR light source. We achieved absolute optical-frequency synthesis by using an optical ring circuit with our filter. We also demonstrated total sweep frequency expansion by switching the longitudinal modes of the DBR laser. The achieved circulation number was 1200, which corresponds to a total sweep frequency of 144 GHz with higher SNR than 30 dB.

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