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A novel fiber laser source for optical generation of highly stable tunable RF/microwave frequency signal

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Abstract: A new approach, i.e., a CW dual-frequency Brillouin fiber laser pumped by two independent single-frequency Er-doped fiber lasers, was demonstrated for the generation of tunable low-noise RF/microwave optical signals, which have the Hz-level frequency stability.

OCIS codes: 060.2840 (Heterodyne); 060.5625 (Radio frequency photonics); 140.3510 (Lasers, fiber); 290.5900 (Scattering, stimulated Brillouin)

1. Introduction

There are numerous industrial and military applications requiring radio frequency (RF) or microwave modulated optical sources that can generate tunable RF/microwave sub-carriers with high frequency stability. These applications include optical/wireless communications, high-speed opto-electronics characterization, millimeter/sub-millimeter-wave phased-array radar, remote distributed antenna system, and hybrid Lidar/Radar system. The RF/microwave photonic technologies also enable optical fiber delivery of timing or RF/microwave frequency references over long distances, which has recently been received intense interest.

An obvious way to the generation of RF/microwave modulated optical signals is to optically heterodyne two laser lines with emission frequency separated by the required modulation frequency. The modulated optical signals can be tuned if the laser lines are tunable. Two different approaches have been used to generate the heterodyning frequency beat, either by two independent laser sources or by a single laser source with dual-frequency output. The major advantage of the first approach is the flexibility in wavelength and power control through two independent lasers, however, it suffers from the fact that the performance of the generated RF/microwave signal is determined by not only phase noise or linewidth of the two lasers but also any relative frequency drift between them. The relative frequency drift can be significantly reduced if a frequency-offset locking scheme is implemented in the system by using an external reference. The development of this kind of RF/microwave optical sources includes the use of distributed-feedback (DFB) semiconductor lasers [1] and diode-pumped solid-state lasers (including fiber lasers) [2]. Since a fiber-based source at the telecom wavelength is especially attractive due to its capability of long-distance delivery and distribution of timing or frequency references over optical fiber, in addition to its compactness and reliability, semiconductor DFB lasers could be good candidates for such a fiber-based source. However, their relatively high phase noise significantly limits the frequency stability of the DFB-laser-based RF/microwave sources. Although active frequency locking can be applied to the DFB lasers for noise reduction, requirements for the frequency locking loop in these lasers are extremely stringent due to the relative broad spectral linewidth (~1MHz) of DFB lasers. Diode-pumped single-frequency solid-state lasers have narrow spectral linewidths (at kHz level) that offer high frequency stability. Higher frequency stability can further be obtained in those diode-pumped single-frequency solid-state lasers if a frequency-locking scheme (to either an external resonator or a frequency reference) is used. For example, the frequency stability at the sub-Hz-level of a microwave modulated laser source was demonstrated, in which two diode-pumped Nd:YAG non-planar ring oscillators (NPRO) were frequency locked to adjacent axial modes of a supercavity (a very high-finesse (F=22,000) interferometer) [3]. However, the requirement for the frequency-locking scheme is stringent (need either a supercavity, or a highly stable frequency reference [4]). In the second approach, in which the two laser lines come from two laser modes sharing a common cavity and common gain [5], its major advantage is that most noise processes originated with the same laser cavity can be cancelled out. However, the power and wavelength of the two laser modes that share the same cavity are not easily controlled independently.

We demonstrate a new approach, i.e., a CW dual-frequency Brillouin fiber laser pumped by two independent single-frequency Er-doped fiber lasers, for the generation of tunable low-noise RF/microwave signals. The new approach combines all the major advantages of the two mentioned -above approaches together. In addition, the inherent feature of noise reduction and linewidth narrowing effect in a Brillouin fiber laser [6][7] allows us to achieve extremely high frequency stability without using a supercavity. The pump scheme in this approach is also different from that in the dual-wavelength Brillouin fiber laser recently reported by Dennis [8]. Our new scheme provides a flexible tuning feature with a much wider tuning range for the RF/microwave modulated optical signals.

2. Experimental

The experimental setup is shown in Fig. 1, which was modified from a single-frequency Brillouin fiber laser [6]. Two similar high-power (~150mW) Er-doped single-frequency fiber lasers with a spectral linewidth of a few kHz and a free-running frequency stability of better than 10MHz/hour at 1550nm were used to pump a single Brillouin fiber laser simultaneously after beam combination with a 3-dB fiber coupler (C1). Both Er-doped fiber lasers are thermally and piezo-electrically tunable with tuning sensitivities of approximate 1.4 GHz/^{o}C and 20 MHz/V, respectively. The Brillouin fiber ring laser is formed by another directional fiber coupler (C2) and long piece of optical fiber (~20m), which are integrated in a temperature-controlled and vibration-damped package.

Laser frequencies of the two Er-doped single-frequency fiber lasers were actively stabilized to be resonant with two cavity modes of the Brillouin fiber laser by using two independent sets of feedback servo, which are based on the Pound-Drever-Hall frequency-locking technique as described in detail before [6]. Dithering frequencies (f_1 and f_2) of the two feedback servos were set to be different (for example, at 1kHz and 1.3kHz, respectively) so that there was no interference between the two feedback servos. Stable dual-frequency operation can be achieved simultaneously by sharing the same Brillouin ring cavity. Output power of the Brillouin fiber laser at each frequency was balanced at about 10mW. Both frequencies of the laser can be independently tunable over multi tens GHz by thermally tuning the pump wavelengths. Assuming that m_1 and m_2 be the mode order of the Brillouin laser cavity of the stimulated Brillouin Stokes beams generated by the two Er-doped fiber lasers, respectively, the frequencies (ω_1 and ω_2) of the two Brillouin Stokes laser beams are given by,

$$\omega_1 = m_1 \times FSR \qquad (1)$$

$$\omega_2 = m_2 \times FSR \qquad (2)$$

where FSR represents the free spectral range of the Brillouin cavity. Therefore, the modulated RF/microwave frequency of the Brillouin laser beam is,

$$f_{RF} = n \times FSR \qquad (3)$$

where n is the mode order difference between the two Brillouin laser components. It is easy to tune the modulation frequency by changing either one of the mode order m_1 and m_2. This can be achieved simply by thermally tuning either wavelength of the two Er-doped fiber lasers.

In the experiment, the FSR of the Brillouin fiber ring cavity was approximately 9.9MHz. Figure 2 shows a typical RF beat note spectrum measured with an ESA (Agilent E4401B). The RF frequency was measured at 999.942MHz, which corresponds to n=101. The observed linewidth was limited by the resolution bandwidth (1 kHz) of the ESA that we used.

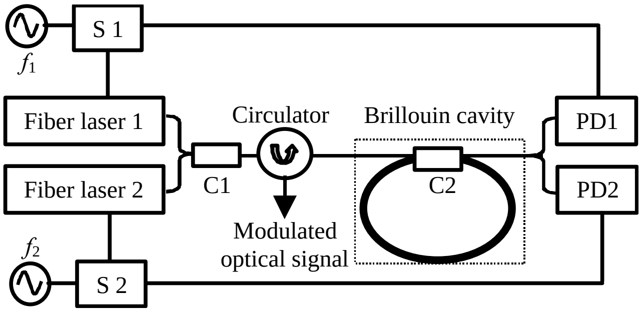

Fig. 1. Experimental setup for the generation of low -noise RF/microwave optical signal. S: feedback servo; C: fiber coupler; PD: photodiode.

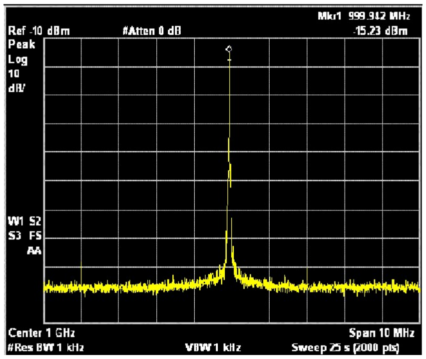

Fig. 2. Typical RF beat note spectrum measured with an ESA (Agilent E4401B). The RF frequency was measured at 999.942MHz, which corresponds to n=101.

The RF beat note frequency can be widely tuned while thermally tuning either wavelength of the Er -doped fiber lasers. Since each of the Er-doped fiber lasers has at least 50-GHz thermal tuning range (corresponding to 35^{o}C temperature change approximately), the modulated RF/microwave frequency from the Brillouin laser can be easily tuned over 100GHz. Higher beat frequency (up to THz region) can also be generated in the same way if the wavelengths of the two Er-doped fiber lasers are set to be far enough. Figure 3 shows that the beat note frequency can be set to be any frequency at an integral multiple (n, i.e., the mode order difference of the dual-frequency components) of the cavity FSR. Interestingly, however, the "effective FSR" of the dual-frequency Brillouin fiber laser, which is defined as the measured beat frequency divided by the integral n, is not a constant over integral n. When the integral n is small that means the two laser frequencies get close, the "effective FSR" is reduced. The "effective FSR" approaches to a constant when the two laser frequencies get separated far enough. This phenomenon can be readily explained by the Brillouin slow light effect [9]. When the frequency difference between the two lasers is comparable to or smaller than the Brillouin gain bandwidth in fiber, either one of the dual-frequency Brillouin laser outputs can experience an additional Brillouin gain generated by the other pump laser. According to the Kramers-Kronig relations, this additional Brillouin gain results in a substantial change in refractive index, thereby yielding a reduced group velocity of light in the dual-frequency Brillouin fiber laser. This explanation is supported by the fact that the 40-MHz FWHM bandwidth of the "effective FSR" profile observed in Fig. 3 is consistent with the natural Brillouin bandwidth in the single-mode fiber at 1.55μm, which is also the bandwidth of Brillouin slow light [9]. From the data in Fig. 3, we know that the maximum change in refractive index in the dual-frequency Brillouin fiber laser is about 0.4%. The Brillouin slow light effect has no impact on the stable operation of the dual-frequency Brillouin fiber laser.

Performance of the RF beat signals generated from both the dual-frequency Brillouin fiber laser and the two Er-doped pump lasers was characterized by using a frequency counter (Stanford Research System, SRS620). Figure 4 shows the root Allan variance of typical RF beat signals (at 148.5 MHz) as a function of sampling gate time. The number of samples for the measurements was 100. As a comparison, the root Allan variances of the RF beat signals between the two Er-doped pump lasers are also shown in Fig. 4. The two pump lasers were operated under two conditions, respectively, i.e., free-running operation and frequency locking (to cavity modes of the Brillouin ring resonator) operation. The root Allan variance of the RF beat signals generated from the dual-frequency Brillouin fiber laser goes down to a few Hz when the sampling gate is longer than 10 seconds, which is three orders of magnitude smaller than that of the two Er-doped fiber lasers even in the operation mode of frequency-locking. The high frequency stability of the beat signal can be attributed to the inherent features of both noise reduction (linewidth narrowing effect) and noise cancellation between two laser modes sharing a common cavity in the dual-frequency Brillouin fiber laser. This new approach for generation of widely tunable, extremely stable RF/microwave frequency could be useful in many applications.

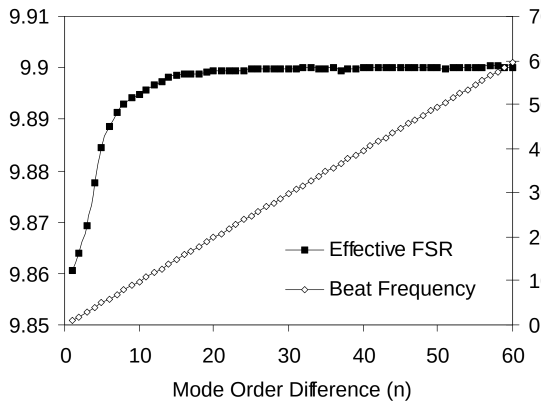

Fig. 3. The measured "effective FSR" and beat frequency as a function of mode order difference between the dual frequencies.

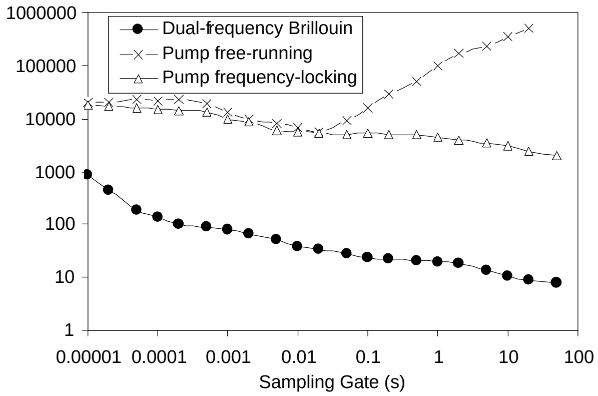

Fig. 4. Root Allan variance of the RF beat signals (at 148.5 MHz) generated from the Brillouin laser.

3. References

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