Tunable microwave generation using dual-wavelength Brillouin O-band fiber laser

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Abstract: A dual-wavelength fiber laser with a tunable output for generating microwave signals is proposed and demonstrated. The system utilizes stimulated Brillouin scattering inside a dispersion compensating fiber to generate the desired dual-wavelength output, which then beats to form the desired microwave frequency in the O-band region. A constant channel spacing of 0.072 nm is obtained for wavelengths ranging from 1260.0 nm to 1330.0 nm. The resulting microwave signal can also be tuned from 13.0 GHz to 12.3 GHz is achieved by controlling the Brillouin pump wavelength, and has a stable signal-to-noise ratio of 30.0 dB.

1. Introduction
Microwave and sub-millimeter wave carrier signal generation through optical sources has been the focus of significant research efforts due to their wide range of applications that range from broadband wireless access networks to applications that involve phased-array communications, radio astronomy and electronic warfare [1]. Traditionally, these signals were generated electronically, but incur high levels of complexity and significant cost. Furthermore, most applications require the generation of the microwave signal on-site, as distribution through electrical lines is not suitable due to high loss [2]. These factors make the electrical generation of microwave and sub-millimeter wave carrier signals highly unpractical, and only used when no other options abound.

In this regard optical fibers, with their inherently low loss and significantly broad bandwidth, make the generation and distribution of microwave signals over optical fibers a very desirable option. Numerous techniques have been proposed and demonstrated for the generation of microwave signals using optical fibers, including optical injection locking [3], optical frequency or phase locked loops [4], external modulation and semiconductor lasers that have been resonantly enhanced [5]. Optical heterodyning has been proven to be an effective and cost-friendly solution towards generating optically based microwave signals, simply by having two lasing signals at different wavelengths mixing at a photodetector to produce an electrical beat signal [6]. The difference between the wavelengths corresponds to the desired microwave frequency.

As a result of this, dual-wavelength fiber lasers (DWFL) have come to the forefront of research as these systems are capable of producing two phase coherent signals whose wavelength difference corresponds to the desired microwave frequency in a compact, cost-effective platform. In addition to this, DWFLs, and by that extension multi-wavelength fiber lasers (MWFLs), can be used to generate a tunable
microwave output. Pan and Yao et. al. reported a frequency-switchable microwave generation using high-finesse ring filter [7], while Kim et. al. demonstrated optical beat frequency generation in an erbium based DWFL utilizing the nonlinear polarization rotation effect [8]. However, a significant concentration of research has been focused on the generation of multi-wavelength and microwave signals at the C-band region, and extending into the S- and L-band regions [7-11], but not much into the O-band region. This provides a promising avenue for research, especially to cater to broader bandwidth as to allow for switchable microwave frequencies [7-8, 12-15].

In this work, a DWFL with a tunable wavelength output operating in the O-band is proposed and demonstrated. The proposed system exploits Brillouin scattering in order to achieve the desired dual-wavelength output, which is used in turn to generate a microwave signal through optical beating. Tunability is achieved by controlling the center wavelength of the Brillouin pump (BP).

2. Experimental Setup
The setup of the proposed O-band DWFL is shown in Figure 1. The system consists of a Santec TLS-550 tunable laser source (TLS), which has a tuning range from 1260.0 nm to 1365.0 nm and acts as the BP for the Brillouin gain medium (BGM). The signal from the TLS is directed through the input port of the first optical circulator (CIR1), and the output from the common port of CIR1 is fed into the BGM. The BGM in this work is a 6.90 km long dispersion shifted fiber (DSF), and its output is connected to a second optical circulator (CIR2), which is configured to act as a reflector by having its output port linked to its input port, thus looping the signal back towards the common port. The output port of CIR1 is connected to a 50:50 coupler, which splits the output signal evenly for analysis by an AQ6370B optical spectrum analyzer (OSA) from Yokogawa, which has a resolution of 0.02 nm, as well as an Advantest U3771 radio frequency spectrum analyzer connected to a Newport 818-BB-51F photodetector.

![Figure 1. Experimental setup of dual-wavelength Brillouin O-band fiber laser.](image-url)
3. Results and Discussion
The desired dual-wavelength output is obtained from the system by exploiting the Brillouin effect in the BGM. In this regard, the TLS serves as the BP. The BP signal then travels into the cavity where it encounters the BGM. The 1st Stokes is generated once the intensity of the BP signal is strong enough to excite stimulated Brillouin scattering (SBS) in the BGM. The Stokes generated is red-shifted by 0.072 nm with respect to the BP wavelength and propagates in the opposite direction. The BP signal continues to travel along the linear cavity where it is reflected by CIR2 and now propagates in the opposite direction, parallel to the 1st Stokes. Thus, two lasing wavelengths are obtained; at 1310.00 nm and 1310.07 nm, with intensities of -7.4 dBm and -5.7 dBm respectively. Due to the structure of the cavity, it is only possible to obtain two lasing wavelengths at any given time, as the structure does not support the generation of the 2nd, 3rd and subsequent Stokes wavelengths. The spectrum of the lasing wavelengths is given in Figure 2.

![Figure 2](image)

**Figure 2.** Dual wavelength output spectrum, showing the BP and 1st Stokes wavelength.

The total output power measured at the output port of CIR1, before reaching the 50:50 coupler, is approximately 1.6 mW, with a laser efficiency of about 16%. The heterodyning of the signal at the photodetector induces a beat frequency at about 12.5 GHz and corresponds to the spacing of 0.072 nm between the two lasing wavelengths. The intensity of the beat signal is about -32.0 dBm, with a signal-to-noise ratio (SNR) of about 30 dB as well. The spectrum of the beating frequency, as captured by the RFSA, is shown in Figure 3.

![Figure 3](image)

**Figure 3.** Beat frequency induced by dual-wavelength Brillouin spectrum.
Figure 4. Time series of the dual-wavelength optical output over a period of 120 minutes.

The stability of the dual-wavelength output and by extension, the beat frequency is shown in Figure 4 and Figure 5 respectively. These measurements were taken over a period of 120 minutes. It can be seen from Figure 4 that the lasing wavelengths are highly stable in the optical domain, with the BP having fluctuations in power of less than 0.5 dB and the 1\textsuperscript{st} Stokes having a power fluctuation of less than 1.4 dB. This is attributed to the fact that the SBS process is highly sensitive to multiple internal and external factors, and can be affected by environmental conditions such as vibrations and temperature. As such, the stability of the 1\textsuperscript{st} Stokes would naturally be slightly less than that of the BP. The beat frequency obtained however is highly stable, with fluctuations of less than 0.01 GHz as given in Figure 5. This indicates that the DWFL, and subsequently the generated microwave signal, is highly stable.

The tunability of the generated frequency is achieved by changing the BP wavelength over a tuning range of 1260.0 nm to 1330.0 nm in increments of 10.0 nm. Since the dual-wavelength output is obtained by the SBS process, thus the spacing between the BP and the 1\textsuperscript{st} Stokes for any BP wavelength will remain unchanged.
Figure 5. Time series of the dual-wavelength fiber laser electric output over a period of 120 minutes.

Figure 6(a) and 6(b) shows the obtained dual-wavelength output against BP wavelength. It can be seen that the dual-wavelength output responds almost linearly to the BP wavelength, which is as predicted. A dual-wavelength output is observed throughout the tuning range of 1260.0 nm to 1330.0 nm, with fluctuations of less than 1.4 dB in the peak powers.

Figure 6. (a) Response of dual-wavelength output against different Brillouin pump wavelengths and (b) Beat frequency shifting corresponded to Brillouin pump wavelength tuning.

Tuning the BP to different wavelengths also results in the tuning of the generated beat frequency, as given in figure 7. By tuning the BP to 1260.0, 1270.0, 1280.0, 1290.0, 1300.0, 1310.0, 1320.0 and 1330.0 nm, a beat frequency of 13.0, 12.9, 12.8, 12.7, 12.6, 12.5, 12.4, and 12.3 GHz respectively was obtained. The output frequencies were observed to have fluctuations of 4.6 dB throughout the tuning range. The fluctuations are attributed to uneven wavelengths and the corresponding frequency response at
photodetector. The proposed system has high potential for use in the O-band region, covering the portion of the spectrum that is still crucial but often overlooked in research efforts. Microwave signal generation corresponding to the 1310.0 nm region is crucial in supporting various telecommunication and scientific applications.

4. Conclusions
A tunable DWFL for microwave signal generation in the O-band region is proposed and demonstrated. The system uses a TLS to launch a BP signal into a 6.9 km long DSF to induce SBS in the system. A dual-wavelength spectrum, tunable from 1260.0 nm to 1330.0 nm with a constant channel spacing of 0.072 nm is obtained, and a beat frequency of 12.5 GHz with an SNR of approximately 30.0 dB is achieved. The output is highly stable in both the optical and electrical regimes, and thus have multiple highly potential applications in a multitude of real-world applications.

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