Continuous Tunable Terahertz Wave Generation via a Novel CW Optical Beat Laser Source

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Abstract: A novel technique of generating two colors or dual-wavelength in a fiber hybrid compound-ring resonator is discussed. Generation of continuous-wave terahertz radiation is demonstrated by using a dual-wavelength widely tunable C-band SOA-based fiber compound-ring laser as a light source, which excites a continuous-wave terahertz photomixer operating at 1.55 µm telecom optical wavelengths. The proposed dual-wavelength fiber laser has a hybrid compound-ring resonator structure and external reflectors that allow output power upscaling and single or dual-output port operation, respectively. Wavelength selection and continuous tunability are achieved by a widely tunable optical filter sandwiched between two fiber-Bragg grating filters of similar Bragg center wavelength. The difference wavelength tuning range of 20.42 nm (i.e., 2.51 THz) is demonstrated in the C-band. Continuous-wave terahertz radiation with continuous tunability between 0.8 and 2.51 THz at room temperature using only a fiber laser source is achieved via photomixing.

1 INTRODUCTION

The development of efficient terahertz (THz) systems using a combination of electronic and optical technologies is an ongoing and important research topic. THz waves have potential applications in sensing and imaging because different materials have highly distinguishable spectral fingerprints due to their enhanced molecular and atomic rotational and vibrational resonances in the terahertz frequency band. Because the THz band has low photon energy levels of 0.41 and 41 meV at frequencies of 0.1 THz and 10 THz, respectively, it is not as harmful as X-ray. Furthermore, compared to X-ray radiation, terahertz waves are more suited for high-resolution sensing and imaging. Due to its non-ionizing nature, it can be exploited in various fields and applications, such as biomedical (Pickwell et al., 2006) and security screenings (Karpowicz et Al., 2005). The THz band can penetrate different materials (Tonouchi, 2007) and hence the widely ranging applications in food, drug and quality control of semiconductor (Hu et al., 1995); (Yamashita et al., 2005).

Generation of THz radiation via laser sources can be classified into two categories: pulsed and CW-THz systems. Pulsed THz systems are more complex than that of their CW THz counterparts. Agility, high scanning speed, high resolution, and simplicity of data processing (Karpowicz et al., 2005; Mickan et al., 2000) are other attributes of the CW terahertz generating system. Typically, the CW-THz system uses two CW laser sources; one with a fixed wavelength and another with a tunable wavelength. In such systems, CW-THz radiation is emitted when the two laser sources with slightly different wavelengths (i.e., beat signal) combine either in a THz- photomixer or a nonlinear optical crystal. The difference wavelength can be tuned over a range of several nanometers that covers a range of frequencies in the terahertz gap (Preu et al., 2011). Some of the CW laser sources used for driving the THz-photomixer are distributed feedback (DFB) laser diodes (Kim et al., 2009), QCLs (Kumar, 2011), and group III-V lasers (Fischer et al., 2009). Because such systems require at least two laser sources, the experimental setups are relatively costly.

Although the approach of combining two independent CW laser sources has facilitated significant advancements of CW-terahertz systems, they still suffer from the negative effects of noise mixing from both CW laser sources and frequency instability which affects the beat frequency signal generated by the photomixing of two slightly different wavelengths. One of the noise reduction

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techniques is to employ external modulators (Frankel et al., 1998) which mitigates the uncorrelated noises from mixing two independent CW lasers. Hence, a single laser source with dual-wavelength, dual-frequency, and dual-multimode operation has been the best solution to avoid the implementation of external systems that are used for reducing noise and frequency drift in CW-terahertz systems (Gu et al., 1999; Kim et al., 2011; Morikawa et al., 1999; Belkin et al., 2008).

Most of the current fiber-based laser systems for CW-terahertz photomixing remain large, inefficient, and expensive. To achieve sufficient pump power to excite a photomixer, large erbium-doped fiber amplifiers (EDFAs) are typically used in linear cavities or single-ring cavities. However, semiconductor optical amplifier (SOA)-based laser systems are more attractive than rare-earth-doped fiber laser systems for several reasons; the main one is the SOA's low cost, footprint, and high efficiency.

In addition to high resolution and high scanning speed properties of CW-terahertz systems, continuous-wave laser sources typically are smaller in size and less expensive (Shibuya et al., 2007). High availability of fiber-based optical components in the telecom-based wavelengths of fiber communications has led to cost and size reductions, as well as increased efficiency of CW-terahertz systems (Carpintero et al., 2015). Current CW fiber laser systems consist of a single output port with fixed optical power. However, the output power scalability and widely continuous wavelength tunability properties of a dual-wavelength fiber laser source are of great interest in developing user-friendly and efficient CW THz systems.

We propose using the passive beam combining method in compound-ring resonators as demonstrated recently (Ummy et al., 2017) with dual-wavelength instead of single wavelength operation. The use of nested compound-ring cavities to split circulating beams equally into N-number of low power beams for amplification by N-number of low power SOAs leads to a highly efficient and high-power laser system that eliminates extra pump lasers, and other expensive external high power optical components. Typically, the generation of tunable dual-wavelengths at telecom optical wavelengths in a single laser source is achieved by using a photonic crystal fiber (Soltanian et al., 2015), FBG filters (Dong et al., 2016), a Fabry-Perot filter in conjunction with an optical band-pass filter (Pan et al., 2008), a fiber double-ring filter (Fan et al., 2016) and an array waveguide grating (Ahmad et al., 2012). Most of the aforementioned methods require the use of circulators. Moreover, AWGs are not continuously tunable (i.e., fixed wavelength channel separation) and their tuning range is limited to around 12 nm range. Thus, in the C-band, three different laser sources are used to achieve a wide tuning range of CW-THz radiation without any gaps (Deninger et al., 2014).

In this work, we demonstrate a novel technique of dual-wavelength selection with continuous tunability over the C-band of 20.42 nm at room temperature, which has the potential of generating widely tunable CW-THz radiation via photomixing. Furthermore, we explore the coherent beam combining method based on the passive phase-locking mechanism (Bruesselbach et al., 2005) of two C-band low power SOAs-based all-single-mode fiber hybrid compound-ring resonator by exploiting beam combining (i.e., interference) at 3dB fiber couplers that connect two parallel nested ring cavities. As opposed to using multiple laser sources (i.e., three CW laser sources) we achieve a wide tuning range of CW-THz radiation by using single laser source. The proposed dual-wavelength fiber laser source is used as a single source to excite a CW-THz photomixer where CW-THz radiation is generated and detected using a CW-THz photomixer and pyroelectric based THz sensor. We had successfully generated THz radiation from 0.8 and 2.51 THz at room temperature.

2 EXPERIMENTAL SETUP

Fig. 1 illustrates the experimental setup of the C-band SOA-based tunable fiber laser with two nested ring cavities (i.e., hybrid compound-ring resonator) and two broadband SLMs that can serve as either dual-output ports or a single output port depending on the reflectivity of each SLM. Each ring cavity is comprised of two branches: I-II and I-III, for the inner and the outer ring cavity, respectively. Both ring cavities share a common branch, I, which contains an SOA, SOA_1 (Kamelian, OPA-20-N-C-SU), a tunable optical filter (TF-11-11-1520/1570) sandwiched between two similar FBGs, and a polarization controller, PC_1. Branch II contains SOA_2 (Thorlabs, S1013S), and a polarization controller, PC2. Due to the lack of availability of a third SOA, branch III only contains a polarization controller, PC_3. As Fig. 1 portrays, all branches are connected by two 3dB fiber couplers, C_1 and C_2, which are connected to SLM_1 and SLM_2, correspondingly. Each SLM, SLM_1 and SLM_2, in conjunction with a PC (PC_4 and PC_5, respectively) acts as a variable optical reflector. By adjusting PC_4 or PC_5, one can manipulate the reflectivity of SLM_1 and SLM_2, respectively, and switch between single and dual-output port configurations.

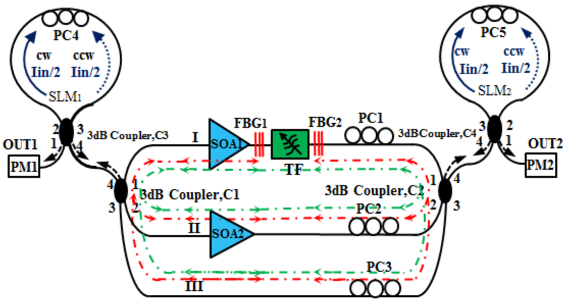

Figure 1: Experimental setup of the dual Sagnac loop mirror dual-wavelength SOA-based tunable fiber hybrid compound-ring laser.

Sandwiching the low power tunable optical filter (TF) in the common branch, I, between two similar FGBs centered at 1551.98 nm, one of which is fixed at 1551.98 nm and the other which is tunable up to 1572.42 nm, allows for dual wavelength selection. The three PCs (PC_1, PC_2, and PC_3) control the state of polarization of the light circulating within the compound ring cavity.

3 PRINCIPLE OF OPERATION

Generation of a continuously tunable dual wavelength (i.e., two colors) was achieved in a hybrid compound-ring resonator using two fiber Bragg grating filters, FBG_1 and FBG_2, of the same Bragg wavelength (i.e., $\lambda_{FBG1}=\lambda_{FBG2}$) and a widely tunable optical filter, TF, of transmittance spectra. The fixed wavelength is selected by the FBGs, and the tunable wavelength, λ_{TF}, is selected by the TF. The wavelength selection is performed in the common branch, I, of the hybrid compound-ring cavity.

The principle of operation of the proposed fiber laser is as follows: assume that both semiconductor optical amplifiers (SOAs) are driven above the threshold bias current level, and the reflectivity of each output coupler formed by a Sagnac loop mirror (i.e., SLM_1 and SLM_2) is adjusted to ≤0.1%. When the pump level (i.e., bias current level) of either SOA is more than the total fiber compound-ring cavity losses, amplified spontaneous emission (ASE) emitted from the SOAs propagates in the forward and backward directions. For instance, when a bias current, I_B, of approximately 75 mA is injected into SOA_1 (branch I), the emitted ASE emitted by SOA_1 circulates in a clockwise (cw) direction. The clockwise propagating ASE reaches the FBG_1 filter, which reflects a fixed wavelength, λ_{FBG1}, back into SOA_1 while the remaining ASE signal propagates through the tunable filter, TF, which selects a tunable wavelength λ_{TF} and rejects the rest of the ASE spectrum. The selected tunable wavelength, λ_{TF}, is different from the Bragg wavelength of the FBGs. Thus, the selected beam with tunable wavelength, λ_{TF}, passes through the FBG_2 filter and polarization controller PC_1 before it reaches port 1 of the 3-dB fiber coupler, C_2, where it is equally split (i.e., 50% goes to port 2 and port 3, respectively) and is coupled into branches II and III of the fiber compound-ring cavity. Half of the selected beam that propagates into branch II passes through polarization controller $PC_2$and is amplified by SOA_2 (i.e., when its bias current level is above 180 mA) before it arrives at port 2 of the 3-dB fiber coupler C_1, where the amplified signal is also equally split between port 1 and 4 after being combined with the beam at port 3 that propagates through branch III. Half of the selected beam at port 4 of the 3-dB fiber coupler C_1 is fed into the output coupler, SLM_1. As the reflectivity of SLM_1 is set at ≤0.1%, the selected beam with λ_{TF} exits at port 1 (i.e., OUT1) of the 3-dB fiber coupler, C_3. The other 50% of the selected beam coupled into port 1 of the 3-dB fiber coupler C_1 is further amplified by SOA_1. Therefore, this closes the ring structure, completes a round trip in the clockwise direction and allows lasing to occur at tunable wavelength λ_{TF}.

As mentioned earlier, the wavelength, λ_{FBG1}, selected by the FBG_1 is reflected back and propagates in the counter-clockwise direction through SOA_1, where it is amplified and is equally split by the 3-dB fiber coupler C_3 and is coupled (i.e., 50% each) into branches II and III of the fiber compound-ring cavity. 50% of the selected beam with fixed wavelength, λ_{FBG1}, propagates in branch II and is further amplified by SOA_2, while the other 50% propagates through branch III. Both light beams propagate through polarization controllers, PC_2, and PC_3, respectively, before being combined and equally split at ports 1 and 4 of the 3-dB fiber coupler C_2. Half of the selected beam at port 4 of the 3-dB fiber coupler C_2 is fed into the other output coupler, SLM_2, which then exits from port 1 (i.e., OUT2) of the 3-dB fiber coupler, C_4. The other 50% of the beam with the selected wavelength, λ_{FBG1}, that is coupled into branch I reaches the other fiber Bragg grating filter, FBG_2, and reflected back toward the 3-dB fiber coupler, C_4. There, it is equally split and is respectively coupled into branches II and III for further amplification which leads to lasing of the fixed Bragg wavelength, λ_{FBG}, after it traces its round trip back to the FBG_1 filter while going through further amplification by SOA_1 and SOA_2.

Note that as there is no optical isolator, the same wavelength selection of λ_{TF} and λ_{FBG1} occurs from the counter-clockwise propagating ASE, where the selected wavelengths λ_{TF} and λ_{FBG1} circulate in the counter-clockwise and clockwise directions and exit at the output couplers, SLM_2 and SLM_1, respectively. Thus, two lasing wavelengths (i.e., tunable λ_{TF} and fixed λ_{FBG}) coexist in the fiber hybrid compound-ring cavity, and they are extracted at both output couplers, OUT1 and OUT2. If the reflectivity of output coupler SLM_1 is set to maximum (i.e., ≥ 99.9%), then the light beam of dual wavelength exits from the output coupler SLM_2, or vice versa. The wavelength separation (i.e., $\Delta\lambda_{THz}$) is controlled by continuously adjusting the tunable filter, TF. An optical spectrum analyzer (OSA), variable optical attenuator (VOA) and optical power meter (PM) were used to characterize the proposed fiber hybrid compound-ring laser. Note that the path lengths of both loops are almost the same since all branches have identical length and all fiber connections utilize FC/APC connectors.

4 DUAL-WAVELENGTH TUNABILITY AND POWER STABILITY

We first set the bias currents for SOA_1 and SOA_2 at 200 and 500 mA, respectively. The reflectivity of SLM_1 and SLM_2 were set and kept constant at ≤ 0.1% and ≥ 99.9%, respectively. Then, the dual-wavelength signal of the output light beam was measured with an OSA. The wavelength separation (i.e., wavelength beat signal) was tuned by manually adjusting the tunable filter, from 1554.98 nm to 1572.33nm while simultaneously optimizing the polarization controllers, PC_1, PC_2, and PC_3, at each wavelength. Moreover, as mentioned, the fixed wavelength was selected by two FBG filters, which are centered at 1551.98 nm. Fig. 2 shows wavelength separation (i.e., beat signal: $\Delta\lambda_{THz}= \lambda_2-\lambda_1$) of 3 nm, and 20.35 nm, which corresponds to CW-THz beat frequencies (i.e., $\Delta\upsilon_{THz} = c*(\Delta\lambda_{THz}/(\lambda_1*\lambda_2))$) of 0.37 and 2.5 THz, respectively.

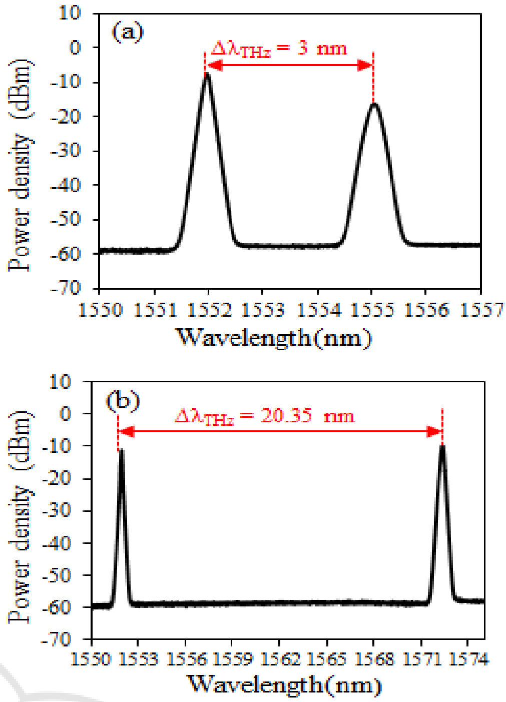

Figure 2: Illustrates the wavelength spectrum of the dual-wavelength fiber hybrid compound-ring laser. (a) and (b) show wavelength separation between the fixed and tunable wavelength of 3 nm and 20.35 nm, respectively.

The peak signals deducted from the measured output wavelength spectra by using an OSA (e.g., Fig.2) were used to determine the optical signal-to-noise ratio (OSNR). We subtracted the peak power value at each center wavelength from the background noise level of each wavelength spectrum. The OSNR for the fixed wavelength and tunable wavelength remained well above +50 dB and +45 dB over the whole wavelength tuning range, respectively.

We performed a short-term optical power stability test at room temperature with SOA_1, and SOA_2 set at the standard bias current levels of 200 and 500 mA, respectively. The optical power stability test was carried out over a total duration of 180 minutes with three-minute intervals and an OSA resolution bandwidth of 0.01 nm. Fig.3 demonstrates that the proposed fiber hybrid compound-ring laser whose power fluctuations were within ±0.025 dB and could have been further reduced by the proper packaging of the system to make it more stable.

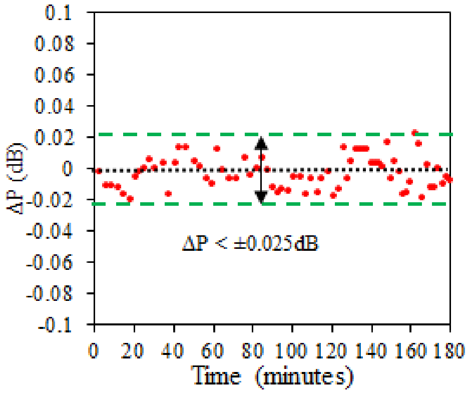

Figure 3: Shows the output power short-term fluctuations measured over three hours at room temperature.

4.1 Generation and Detection of CW-THz Radiation

The proposed tunable fiber laser was used as a light source to excite an off-the-shelf photo-mixer (CW-TH based Indium Gallium Arsenide (InGaAs)) as an emitter and a pyroelectric-based terahertz sensor as a detector. The experimental setup, which is used for generating and detecting CW-terahertz radiation is shown in Fig.4. The bias current of SOA_1 and SOA_2 was kept constant at 250 and 500 mA, respectively. The output power of the laser source was controlled by adjusting polarization controller PC_5 which was placed in SLM_2. We adjusted the PC so that the output power does not exceed 10 mW. A wideband 1x2 single-mode fiber optic coupler with split ratio of 95% and 5% was connected to the output coupler, OUT1, of the laser system. The 95% output port was connected to the CW-THz InGaAs emitter (TX). The 5% output port was connected to an inline power meter, PM, which was used to monitor the excitation power. An optical spectrum analyzer was employed to monitor the output spectrum of the dual-wavelength laser. The tunable filter was manually adjusted in steps of 0.1 nm. Note that an automated continuously tunable filter can be used to achieve an even higher wavelength tuning resolution. The optical beat signal from the laser source was delivered on the terahertz InGaAs-photomixer through a single-mode fiber and FC/APC.

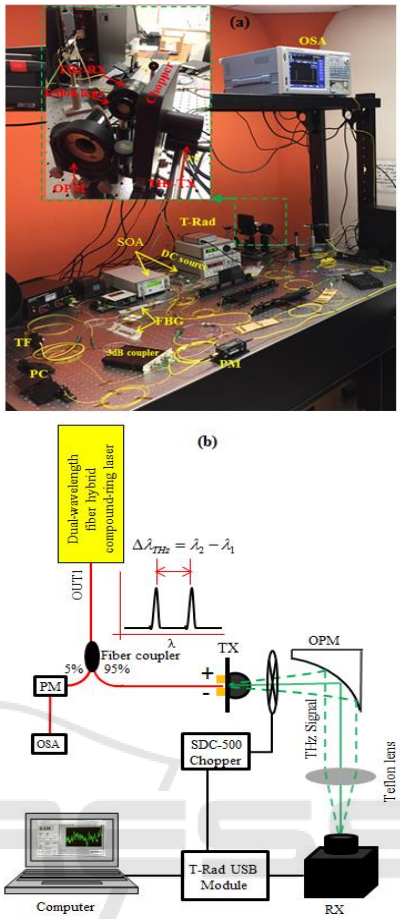

Figure 4: (a) Pictorial view of the experimental setup for CW-terahertz radiation measurements (TX: InGaAs-photomixer and RX: pyroelectric THz sensor) and (b) its schematic diagram.

Most of the terahertz radiation generated by the antenna was radiated through the Indium Phosphide (InP) substrate. Thus, a silicon lens was used to couple the radiation into free space. An off-axis parabolic mirror, OPM, was used to collect and collimate the CW-terahertz signal from the THz emitter. A polytetrafluoroethylene (i.e., Teflon) lens was used to focus the CW-terahertz signal onto the pyroelectric-based terahertz detector, which was calibrated from 0.8 to 30 THz (Gentec-EO, Inc). An optical chopper system, which provided a reference signal of 25.7 Hz chopping frequency to the detector module, was employed to increase the signal-to-noise ratio.

A DC voltage source was used to bias the terahertz InGaAs-photomixer at -1.4 V to increase the terahertz radiation emitted by the photomixer. The utilized CW-THz photomixer has a carrier lifetime of about 0.3 ps and bandwidth of around 3

THz (Globisch et al., 2016). The theoretical bandwidth curve was obtained by using Eq.1 below (Carpintero et al., 2015),

$$P_{THz}(\omega) \approx \frac{A}{1+(\omega\tau)^2} \qquad (1)$$

where A is a constant and τ is the photo-carrier lifetime of photo-induced free-charges.

The CW-terahertz generation ranges from 0.875 to 2.51 THz when the tunable filter is tuned from 1554.98 nm to 1572.33 nm with a filter step size of 0.1 nm. This corresponds to around 1.2 GHz in the C-band.

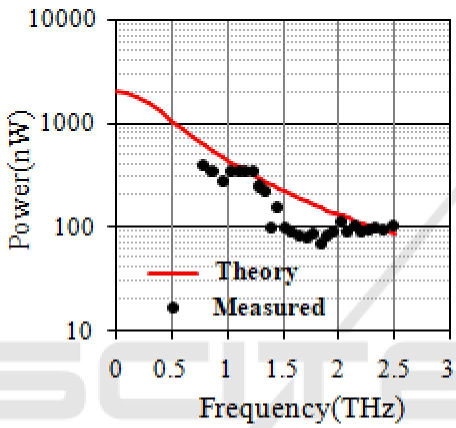

Figure 5: Frequency spectrum of CW-terahertz radiation measured by a pyroelectric terahertz detector and theoretical curve fit with A = 2 µW and τ = 0.3 ps.

The maximum measured average power was around 350 nW around 1 THz as shown in Fig.5. The measured power dropped around 80 nW above 1.5 THz, which is in agreement with the specifications of the utilized CW-terahertz photomixer (TOPTICA Photonics, Inc).

5 CONCLUSIONS

We successfully demonstrated the application of the proposed dual-wavelength C-band SOA- based fiber hybrid compound-ring laser for the generation of continuous-wave terahertz radiation. The proposed fiber laser was used to excite a terahertz InGaAs photomixer. The CW-THz radiation emitted by the InGaAs-photomixer was detected by a pyroelectric terahertz sensor. The largest tuning range, $\Delta\lambda_{THz}$, of 20.42 nm, which corresponds to a CW-THz beat signal (i.e., $\Delta\upsilon_{THz}$) of 2.51 THz, was achieved from the proposed fiber laser source. Continuous wavelength tuning was achieved at room temperature from a single light source, unlike laser systems that require several light sources to achieve the same wavelength tuning range. By using an NxN hybrid compound-ring structure with multiple low power N-number of SOAs or the proposed fiber laser source to provide a seed signal to a high gain semiconductor optical amplifier and using different pairs of FBG filters centered at approximately 1520 nm, one can achieve approximately a 50-nm wavelength tuning range. Such a type of fiber laser system can excite an electro-optic crystal (Soltanian et al., 2015) to generate beat signals, $\Delta\upsilon_{THz}$, that can reach approximately 6THz. To the best of our knowledge, this level of tuning range is far beyond the range of the current commercially available CW THz sources and uses low power optical components.

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