Frequency Tunable Continuous THz Wave Generation in a Periodically Poled Fiber

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***Abstract*—An all-fiber approach to terahertz generation using a periodically poled optical fiber is proposed and experimentally demonstrated. In the proposed approach, a continuous-wave THz wave is generated at a periodically poled fiber by beating two optical wavelengths from two laser sources with the wavelength spacing corresponding to the frequency of the THz wave. The key component in the system is the periodically poled fiber, which is made by a twin-hole fiber with the fiber core residing between two holes. The twin-hole fiber is then thermally poled at a temperature of $\sim$260° C with a voltage of 3.3 kV applied to the silver electrodes inside the two holes to introduce second-order nonlinearity. The quasi phase matching (QPM) condition is achieved by periodically erasing the thermal poling induced second-order nonlinearity with an ultraviolet laser, which enhances the energy conversion efficiency. The proposed approach is validated by an experiment. The emission of a THz wave centered at 3.8 THz with an output power of 0.5 μW is observed. The frequency tunability between 2.2 and 3.8 THz is also experimentally demonstrated.**

***Index Terms*—Difference frequency generation (DFG), fiber nonlinear optics, quasi-phase matching (QPM), second-order nonlinearity, terahertz (THz), thermal poling.**

I. Introduction

TERAHERTZ (THz) waves, covering a frequency range from 100 GHz to 30 THz, are very attractive for noninvasive imaging due to its non-ionizing radiation and penetration of a wide variety of materials. In combination with strong spectral fingerprints of many materials at the THz range, these features allow important applications of THz imaging in medical sciences [1], homeland security [2], and non-destructive evaluation [3]. THz waves can also find applications in ultra-high speed wireless communications [4] because of its ability to provide an ultra-wide bandwidth. Among those applications, an efficient THz source is critical. In the last few years, numerous approaches have been proposed to implement THz sources with low cost, high efficiency, and high output power [5]. At present, there are three major approaches receiving attention for developing terahertz sources. The first is the recently developed THz-quantum cascade laser (THz-QCL) for direct emission of a THz wave. The second is to use an ultra-short optical pulse to generate a THz wave based on optical rectification, which has been extensively studied due to its high conversion efficiency. The third is to beat two optical wavelengths with their frequency spacing falling into the THz regime, which provides a simple solution to THz generation with high reliability and low cost.

In the first category, a THz wave is generated directly from a semiconductor-based QCL. A THz-QCL is a coherent source of THz radiation based on quantum confinement in a semiconductor hetero-structure. The first QCL was developed in 1994 [6] and had a lasing frequency of about 70 THz, which was beyond the THz regime. Recent advances in nanotechnology have led to the development of THz-QCL sources with the capability to generate THz emission with lasing frequencies as low as 1.2 THz, which was achieved based on Cherenkov intra-cavity difference frequency generation (DFG) in a THz-QCL [7].

In the second category, a broadband THz pulse is generated based on optical rectification involving second-order nonlinear optical effects. The generation of a THz pulse from optical rectification of an ultra-short laser pulse is based on difference frequency mixing of all frequencies within the bandwidth of the ultra-short laser pulse. However, the optical rectification is considered as the degenerate case of DFG with the frequency difference close to zero. Recently, ultra-short terahertz pulses have been experimentally generated by optical rectification in an MgO-doped stoichiometric lithium niobate [8] and a cryogenically cooled congruent lithium niobate [9]. THz generation by optical rectification has the unique advantage of a broad spectral bandwidth. It can also provide a high peak power [10], [11].

In the third category, a continuous-wave (CW) THz wave with large frequency tunability can be generated by beating two optical wavelengths at a solid-state device or a nonlinear optical crystal. A solid-state electronic device, such as a uni-traveling-carrier photodiode (UTC-PD), can operate in the lower-frequency end of the THz regime. A THz wave is generated in a UTC-PD by the optical beat of two light waves from two different wavelength laser diodes (LDs), and the emission frequency of the THz wave is defined by the difference between the two wavelengths [12]. By tuning the wavelength difference between the two light waves, the frequency of the THz emission is tunable up to 1.5 THz, and a maximum CW output power of 20 mW at 100 GHz or 10 μW at 1 THz has been achieved [12]. The use of a UTC-PD offers a high efficient THz source

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with a small footprint. However, it only covers the lower frequency end of the THz regime with a low output power. To increase the frequency of the generated THz, nonlinear optical crystals are widely used in THz generation based on DFG. When the DFG process in a nonlinear crystal is phase matched, a coherent THz beam at a high power can be obtained. For example, a tunable coherent THz wave from 1 to 4.5 THz in a nonlinear optical crystal, zinc germanium phosphide, has been achieved with a peak power of 36 W [13]. An optical crystal with second-order nonlinearity is critical to optical DFG, which only exists in non-centrosymmetric crystals. Nevertheless, by breaking the crystal symmetry, DFG can also be achieved in a centrosymmetric crystal, such as Si_3N_4 [14].

In a DFG-based THz generation system, the nonlinear crystal, such as GaAs, GaSe, GaP, ZnTe, CdTe, DAST, and LiNbO3, is the key device and is relatively expensive. To reduce the cost, in this paper we propose to use a periodically poled optical fiber to generate a tunable THz wave by beating two wavelengths with a wavelength spacing corresponding to a THz wave at the periodically poled fiber. The periodically poled fiber is made by a length of twin-hole optical fiber with its fiber core residing between the two holes. After the twin-hole fiber is drawn, two silver electrodes are inserted into the two holes. The twin-hole fiber is then thermally poled at a temperature of $\sim$260°C with a voltage of 3.3 kV applied to the two silver electrodes to introduce second-order nonlinearity into the homogeneous glass, which does not exhibit even-order optical response because of the centrosymmetric nature. An ultraviolet (UV) laser source is then used to periodically erase the thermal poling induced second-order nonlinearity to achieve quasi-phase matching (QPM), which would enhance the energy conversion efficiency. In this way, a THz wave can be effectively generated in the periodically poled optical fiber based on optical DFG.

The paper is organized as follows. In Section II, the principle of the proposed approach is presented, with an emphasis on DFG and QPM in an optical fiber. In Section III, the procedure of preparing the periodically poled fiber is discussed, and an experimental demonstration for THz generation using the proposed periodically poled fiber is presented. A THz wave centered at 3.8 THz with an output power of 0.5 μW is generated, and the frequency tunability between 2.2 THz and 3.8 THz is experimentally demonstrated. A conclusion is drawn in Section IV.

II. Principle

Fig. 1 shows the proposed THz generation system. It consists of two tunable laser sources (TLSs), an optical chopper, a periodically poled fiber, and a THz detector. Two linearly polarized CW light waves from the two TLSs with the same polarization state controlled by tuning a polarization controller (PC) are combined by an optical coupler and sent to the optical chopper, by which the light waves are chopped at a frequency of 10 Hz to synchronize with the THz detector. The two chopped light waves then travel along the periodically poled fiber, where the DFG occurs due to the second-order nonlinearity induced by thermal poling. The emission frequency is determined by the frequency difference between the two light waves, and the emission power is enhanced by the QPM of the periodical second-order nonlinearity in the poled fiber.

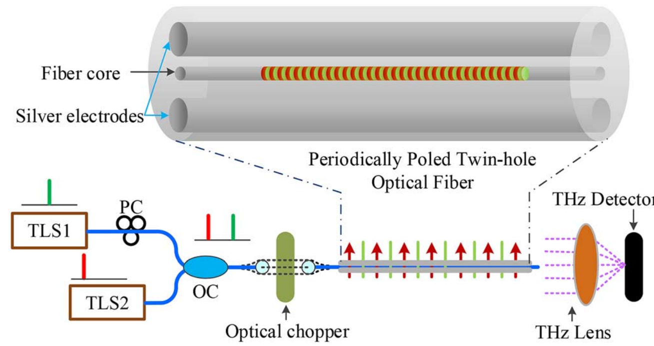

Fig. 1. Schematic of the proposed optical THz generation system. TLS: tunable laser source; PC: polarization controller; OC: optical coupler.

We start our analysis by studying THz generation based on DFG in an optical fiber. The thermal poling of an optical fiber is discussed to introduce second-order nonlinearity for optical DFG in a centrosymmetric silica fiber. To increase the THz power conversion efficiency by optical DFG in a thermally poled fiber, a technique to achieve QPM is discussed, in which a UV light is used to periodically erase the thermal poling induced second-order nonlinearity in the optical fiber. Finally, the use of the periodically poled fiber for tunable THz generation is provided.

A. Difference Frequency Generation

Mathematically, the nonlinear polarization P can be expanded into a power series of the electric field E applied to a nonlinear crystal or nonlinear fiber [15]

$$P = \varepsilon_0[\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \cdots] \tag{1}$$

where ε_0 is the dielectric constant of the vacuum, and $\chi^{(i)}$ is the ith-order nonlinear susceptibility. The optical DFG comes from the second term of (1) which is the second-order nonlinearity.

Assume that two light waves with two angular frequencies of ω_1 and ω_2 are incident into a nonlinear crystal or fiber with a second-order nonlinear susceptibility of $\chi^{(2)}$, and the incident lights are plane waves, then the nonlinear polarization for DFG can be expressed

$$P^{(2)}_{\mathrm{DFG}} = 2\varepsilon_0\chi^{(2)}[E_1E_2\exp(j\Omega t) + E_1^*E_2^*\exp(-j\Omega t)] \tag{2}$$

where E_1 and E_2 are the amplitudes of the electric fields of the two light waves, and $\Omega = \omega_1 - \omega_2$ is the frequency difference between the two light waves. In the far field, the radiated electric field $E_r(t)$ is proportional to the second derivative of $P^{(2)}_{\mathrm{DFG}}$ with respect to time t, given by [16]

$$E_r(t) \propto \frac{\partial^2}{\partial^2 t}P^{(2)}_{\mathrm{DFG}}. \tag{3}$$

As the second-order susceptibility $\chi^{(2)}$ depends on the structure of the crystal. A homogeneous glass, such as a silica optical fiber, has no even-order nonlinearities due to the centrosymmetric nature of the fiber structure. Thus, it is not feasible for THz generation based on DFG in a silica fiber.

However, second-order nonlinearity can be observed in a silica fiber if the fiber is thermally poled [17]. The origin of second-order nonlinearity in a thermally poled silica fiber is due to the electro-optical effect resulted from the interaction between the "frozen" electric field at the near-anode surface and the third-order optical susceptibility of the glass, which can be expressed as [18]

$$\chi^{(2)} = 3\chi^{(3)} E_{\mathrm{dc}} \tag{4}$$

where E_{dc} is the strength of the "frozen" electric field. It can be seen that the thermal poling induced second-order susceptibility is proportional to the third-order susceptibility. To progress toward the use of thermally poled optical fiber in DFG applications, the glass composition of the optical fiber with appropriate third-order nonlinear optical response is necessary for obtaining efficient second-order nonlinearity, and appropriate ionic/electron conductivity to allow an improved charge rearrangement processes during the poling treatment should be considered.

B. Quasi-Phase Matching

Given a second-order susceptibility and two incident light waves, (3) can be used to calculate the far-field electric filed of the radiation. However, many factors, such as absorption, diffraction, phase matching, and saturation, could affect the radiation efficiency, among which phase matching is the most important factor for accumulative energy conversion efficiency [15] in a nonlinear process, such as THz generation based on optical DFG. Phase matching requires conservation of energy and momentum in the nonlinear process, which is described by [15]

$$\begin{cases} \omega_1 - \omega_2 = \Omega \\ k_1 - k_2 = k_{\mathrm{DFG}} \end{cases} \tag{5}$$

where k_1 and k_2 are the wavenumbers of the optical waves involved in the DFG process, and k_{DFG} is the wavenumber of the generated THz wave. Only when phase matching is satisfied, all three waves participating in the optical DFG process can keep in phase and lead to maximum energy conversion coefficient along the light propagation. The coherence length is defined by the interaction length when the phase change reaches π, given by

$$\delta k L_c = \pi \tag{6}$$

where $\delta k = k_1 - k_2 - k_{\mathrm{DFG}}$. To efficiently generate a THz wave from a length of thermally poled optical fiber, the length of the fiber cannot be selected longer than the coherent length in order to avoid conversion cancellation due to phase mismatch [15]. Therefore, the output power of the generated THz wave is limited by the coherent length.

Since the frequency of a THz wave is much lower than the frequency of a light wave, (5) can be simplified [16]

$$\frac{\partial \omega}{\partial k} = \frac{\Omega}{k_{\mathrm{THz}}} \tag{7}$$

where k_{THz} is the wavenumber of the generated THz wave. According to the electromagnetic principle, (7) can be rewritten as

$$v_{\mathrm{Group}} = v_{\mathrm{Phase,THz}} \tag{8}$$

where v_{Group} is the group velocity of the optical beam, and $v_{\mathrm{Phase,THz}}$ is the phase velocity of the generated THz wave. It can be seen from (8) that the phase matching condition requires that the group velocity of the optical beam and the phase velocity of the generated THz wave are identical.

This condition is usually difficult to be satisfied for arbitrary optical frequencies. To achieve QPM in a thermally poled fiber for arbitrary optical DFG, a QPM $\chi^{(2)}$ grating can be fabricated by a UV laser to periodically erase the thermal poling induced $\chi^{(2)}$ [19], and the required QPM period is given from the phase matching condition [15], [20]

$$\Delta k = k_{\mathrm{DFG}} - k_1 + k_2 - \frac{2\pi}{m\Lambda} = 0 \tag{9}$$

where m is the order of the grating period, and Λ is the grating period. Therefore, effective QPM can be achieved in a periodically poled optical fiber to improve the energy conversion efficiency. According to (5) and (9), the frequency of the THz wave, v_{THz}, could be expressed as

$$v_{\mathrm{THz}} = \frac{mc}{\Lambda(n_{\mathrm{THz}} - n_{\mathrm{opt}})} \tag{10}$$

where c is the velocity of light in vacuum, and n_{THz} and n_{opt} are the refractive indices of the THz wave and the incident optical beams in the optical fiber, respectively. As can be seen from (10), the frequency of the generated THz wave can be tuned by using different grating orders. However, the frequency tunability is not continuous.

C. THz Generation

According to the above discussion, a THz wave could be generated based on optical DFG in a length of thermally poled fiber, if the frequency spacing of the two incident optical beams falls in the THz regime. To have maximum energy conversion efficiency, a QPM process with the periodical UV erasure of thermal poling induced $\chi^{(2)}$ could be performed. The collinear phase matching condition is given in (9), where phase matching occurs when the excitation and THz beams collinearly propagate through the periodically poled optical fiber. In this way, the generation of THz not only gives a high energy conversion efficiency due to long interaction length, but also provides a high beam quality.

III. Experiment

To implement the proposed THz generation system based on a periodically poled fiber, four separate steps, fabrication of a twin-hole fiber, thermal poling process, UV-assisted QPM process, and the implementation of THz generation, are carried out. First, a length of a twin-hole optical fiber is fabricated, and two silver electrodes are chemically applied by pumping the Tollen reaction into in the fiber [21]. To increase the thermal poling induced second-order nonlinearity, the twin-hole fiber is designed with asymmetric electrode structure and alkali ions impurity in the core area. Second, the thermal poling process is performed with dual-anode configuration to improve the temperature-stable charge distribution and the experimental repeatability. Third, a UV laser is used to periodically erase the thermal poling induced second-order nonlinearity in the twin-hole optical fiber. In this way, effective QPM can be

TABLE I
SPECIFICATIONS OF THE TWIN-HOLE FIBER

Spec name	Specifications
Core diameter	3.3±0.2μm
Numerical Aperture	0.215
Cladding outside diameter	250±5μm
Hole diameter	75±3μm
Left hole-to-core distance	4±1μm
Right hole-to-core distance	12±1μm
Core material	SiO_2:Al, ~10 ppm Na^+
Cladding material	SiO_2, no Na^+ impurities
Electrode material	Silver

achieved with the matching period determined by the period of the phase mask. Finally, the prepared periodically poled twin-hole fiber is then used to implement the THz generation system as shown in Fig. 1. The details of the experiment are discussed in the following subsections.

A. Twin-Hole Fiber Fabrication

As can be seen from (4), the second-order nonlinear susceptibility is proportional to the third-order nonlinear susceptibility and the strength of the electric field "frozen" in the fiber by thermal poling. Therefore, one approach for enhancing thermal poling induced $\chi^{(2)}$ for silica-based optical fibers is to increase $\chi^{(3)}$. However, $\chi^{(3)}$ is determined by the crystal structure of the material, and it cannot be improved unless other glass materials are used [22].

The other practical approach is to enhance the electrical field inside the optical fiber. First of all, the strength of the "frozen" electric field can be increased by Na^+ doping in the core area. Since the thermal poling procedure consists of heating the optical fiber to an optimum poling temperature (∼250–290°C) [17] and simultaneously applying a strong electric field to the optical fiber core for a sufficiently long time, alkali ions especially Na^+ can be used to increase the electrical field inside the optical fiber during thermal poling due to their high mobility and easy migration through the glass matrix in this temperature range [23], [24]. However, at room temperature, the mobility of the Na^+ ions is very low and the positions determined at the poling temperature are frozen, which enhances the "frozen" electrical field inside the optical fiber after thermal poling. As a result, the impurity of Na^+ in the core area can increase the "frozen" electric field in the fiber. As shown in Table I, the impurity of Na^+ in the core area of the fabricated twin-hole fiber is ∼10 ppm. Second, the effective thermal depletion area can be increased by proper design of the electrode positions. To increase the overlap area between the fiber core and thermal poling depletion regime, the twin-hole fiber is designed to have one electrode closer to the fiber core than that of the other, and the distances between the core and the two electrodes are given in Table I.

To perform effective thermal poling, two silver film electrodes are also inserted into the two holes of the twin-hole fiber as shown in Fig. 2(a) and Table I. The thin silver film is attached to the wall of the two holes along the fiber. With this design, the usable poling length is easily controlled up to 75 cm at the fabrication without additional difficulties of manually inserting long

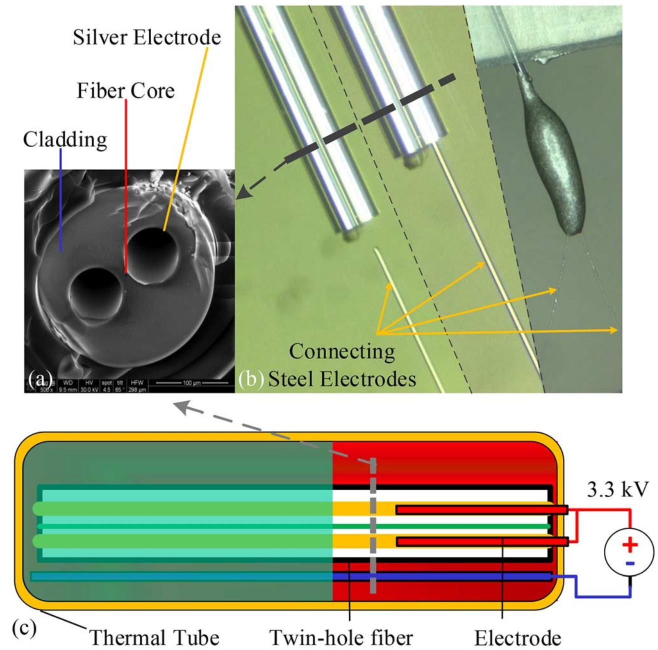

Fig. 2. Thermal poling process. (a) Scanning electron microscope image of the fabricated twin-hole fiber, (b) Dual-electrode insertion process, (c) Schematic of thermal poling setup with dual-anode configuration.

electrodes. However, connecting electrodes are needed for applying voltage to the silver electrodes as shown in Fig. 2(b).

B. Dual-Anode Thermal Poling

The traditional configuration of the two electrodes in a twin-hole fiber for thermal poling is an anode-cathode configuration, with one electrode in the fiber connected to the anode of the source, and the other electrode connected to the cathode of the source. With this configuration, the stability of charge distribution and practical repeatability in the thermal poling process is very limited [25]. In 2009, Margulis *et al.* proposed a new electrode configuration without using cathodes [25], instead, negative charges from the air surrounding the fiber are sufficient for the recording of an electric field across the core of the fiber. An *et al.* also investigated various electrode configurations with experimental demonstrations [26], which indicated that the dual-anode electrode configuration could provide strong and temperature-stable charge distribution, and high practical repeatability.

To prepare for the thermal poling procedure, two external steel electrodes with a diameter of 25 μm are inserted into the two holes of the twin-hole fiber as shown in Fig. 2(b). In Fig. 2(c), the two steel electrodes are then connected to the anode of the high voltage supplier (AHV, G-50), and the cathode of the high voltage supplier is connected to another electrode located outside of but close to the twin-hole fiber. The prepared twin-hole fiber is then placed and kept in a heating oven for 40 min with a temperature of ∼260 °C, and a voltage of 3.3 kV is simultaneously applied to the electrodes. The twin-hole fiber is cooled down with a voltage applied and the nonlinear coefficient d_{33} is also calculated to be 0.4 pm/V in the core based on the measurement of the electro-optic coefficient of the thermally poled optical fiber [25].

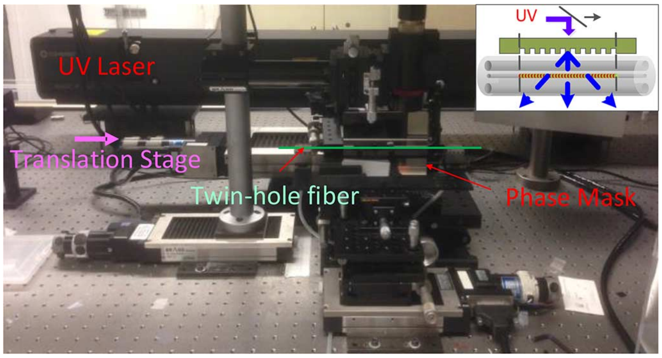

Fig. 3. Experimental setup for periodically erasing of thermal poling induced second-order nonlinearity in the twin-hole fiber.

C. QPM Process

After thermal poling, the QPM process is performed for the twin-hole fiber with a length of 25 cm. Since the thermal poling process would introduce "frozen" SiO^- ions and holes in the fiber core which would lead to the formation of an internal electric field and would thus lead to second-order nonlinearity. However, the UV radiation can destroy the SiO^- ions by the one-photon absorption process [19]. The holes from the conduction band are considered to be trapped at the SiO^- sites and thus the space-charges of the SiO^- ions are neutralized. The induced electric field vanishes with UV laser radiation, which means that the second-order nonlinearity is erased.

As shown in Fig. 3, a CW UV laser (Coherent, Fred 300C) with a wavelength of 244 nm and a power of 35 mW is used to erase the thermal poling induced second-order nonlinearity. The UV laser beam is delivered to a phase mask as shown in Fig. 3 by a translation stage moving with a programmable uniform speed. The twin-hole fiber is placed close to the phase mask with a period of 40 μm. A total UV exposure of 260 min is performed for a QPM length of 20 cm.

To effectively generate THz by using the prepared periodically poled optical fiber, the condition given in (5) should be satisfied. Since the refractive indices for the low frequency end of THz and optical C-band are 1.956 [27] and 1.46, respectively, rewrite (10) for THz generation in the experiment as

$$v_{\mathrm{THz}} = \frac{15.12}{m}\ \mathrm{THz}. \tag{11}$$

It can be seen from (11), the frequency of the generated THz can be tuned by using different grating orders of the QPM grating.

D. THz Generation

As shown in Fig. 4, two linearly polarized CW light waves from the two TLSs (Agilent, N7714A) with the same polarization state controlled by tuning the PC are combined by the optical coupler and then sent to the optical chopper, by which the light waves are chopped at a frequency of 10 Hz to synchronize with the THz detector. The two chopped light waves travel along the periodically poled fiber, where the optical DFG occurs due to the thermal poling induced second-order nonlinearity. The THz radiation is focused by a THz lens (TYDEX, LBX-TPX-D50.8-F50), and detected by the THz detector (Gentec-EO, SPI-D-62). The emission frequency is determined by the frequency difference between the two light waves, and the emission power is enhanced by the QPM of the periodical second-order nonlinearity on the fiber.

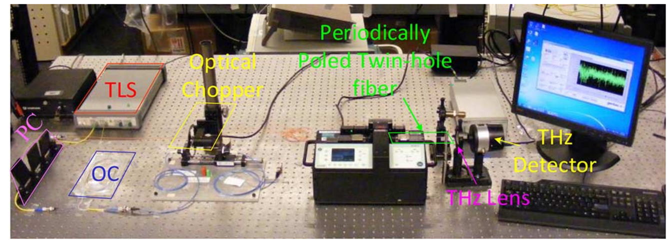

Fig. 4. Experimental setup for the proposed CW THz generation system.

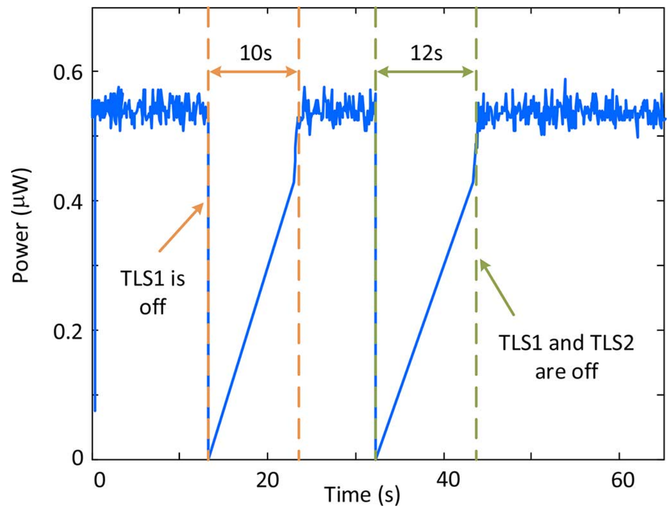

Fig. 5. Generated THz wave with a frequency of 3.8 THz. TLS1 is turned off at the time slot between 13 and 23 s, and both TLS1 and TLS2 are turned off at the time slot between 32 and 44 s.

As shown in Fig. 5, a THz wave with a frequency of 3.8 THz is generated with the incident light waves of 1530.0 and 1560.1 nm, which satisfies (11) with a grating order $m = 4$. To verify the CW THz generation, TLS1 is turned off at the time slot between 13 and 23 s, and both TLS1 and TLS2 are turned off at the time slot between 32 and 44 s. It can be seen from Fig. 5, there is no THz emission detected at both of the two time slots, which confirms the THz generation rather than a leakage of the optical light. Due to the measuring mechanism of the THz detector used in the experiment, no data are collected for a time slot in which the power of a received THz wave is below the trigger power. As a result, a ramp curve is observed in the time slot, which means no data are collected instead of a power change.

The THz power is measured, which is about 0.5 μW. The conversion efficiency is also measured to be 2.9×10^{-5}, which is one order of magnitude higher than that of using an optical fiber with third-order nonlinearity [28], and comparable to that of using other materials [29]. As shown in Fig. 6, the theoretical predication shows an energy conversion efficiency of 4.3×10^{-5} which is higher than the experimentally obtained value of 2.9×10^{-5}. In the experiment, the QPM period variation determined by the phase mask is inevitable, which can decrease the energy conversion efficiency. In addition, the theoretically predicated THz power is higher than the experimentally

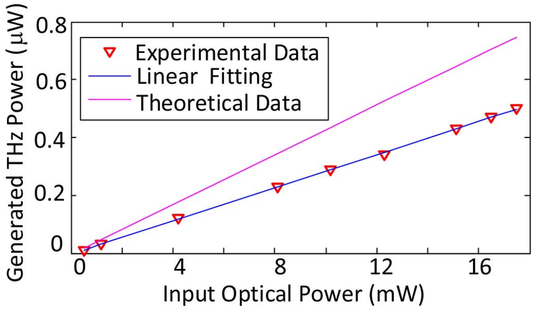

Fig. 6. Output characteristics of the proposed THz generation system at 3.8 THz and compared with the theoretically predicted output power.

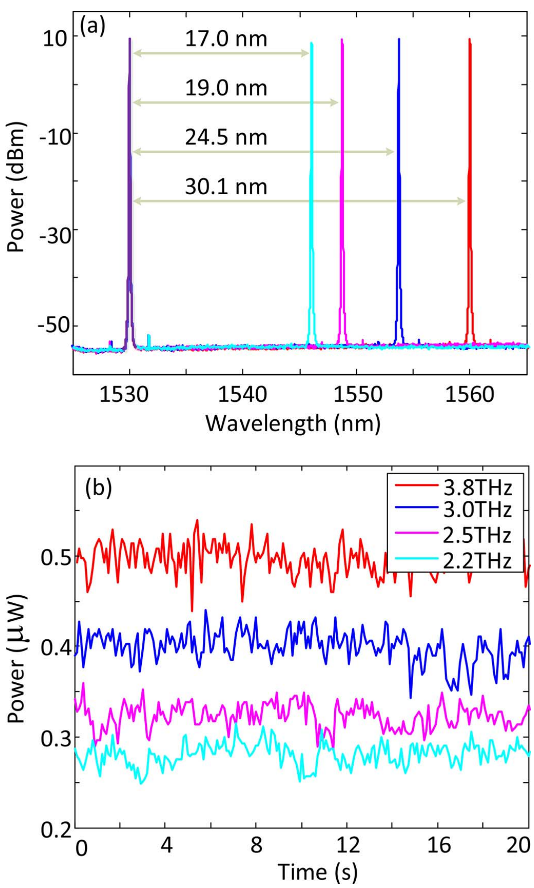

Fig. 7. (a) Optical spectra of different incident light waves. (b) Powers of the THz waves at 2.2, 2.5, 3.0, and 3.8 THz.

obtained value due to the incomplete collection of the THz emission by the THz lens. However, the obtained THz emission in real applications could be improved if the emitted THz wave is completely collected and a longer periodically poled fiber is used. To evaluate the frequency tunability of the proposed system, the wavelength of TLS2, as shown in Fig. 1, is tuned at four different wavelengths of 1547, 1549, 1554.5, 1560.1 nm, while keeping the wavelength of TLS1 at a fixed wavelength of 1530 nm, as shown in Fig. 7(a). The generated THz wave with a frequency of 2.2, 2.5, 3.0, and 3.8 THz is measured by the THz detector, as shown in Fig. 7(b). As can be seen from Fig. 7(b), the power of the generated THz varies for different frequencies, which is due to the use of different grating order of QPM at a different frequency.

In our experiment, the generated THz wave propagates collinearly with the input light waves based on the energy conversation and phase matching conditions [26]. Since the frequency of the generated THz wave is from 2.2 to 3.8 THz corresponding to a wavelength in free space from 136.36 to 78.95 μm, which is smaller than the dimension of the fiber cladding considering the refractive index for THz is $\sim$2, the optical fiber would act as a multimode fiber to support the propagation of the THz wave. However, there are two holes that are attached by two thin silver films in the fiber cladding, the mode propagation for the THz wave can be strongly interrupted due to the reflections on the silver films. Therefore, most of the THz wave energy would be coupled into the free space, and the THz lens can only collect part of the THz radiation. For real applications, the silver films can be removed by a chemical solvent and the two holes in the cladding can be filled by an index matching gel to reduce scattering and propagation loss.

IV. Conclusion

We have proposed and experimentally demonstrated a new and cost-effective approach to achieving tunable THz generation based on DFG using a periodically poled fiber. The key component in the system was the periodically poled fiber, which was made by a twin-hole fiber with the fiber core residing between two holes. The twin-hole fiber was thermally poled at a temperature of $\sim$260 °C with a voltage of 3.3 kV applied to the silver electrodes inside the two holes to introduce second-order nonlinearity. The QPM condition was achieved by periodically erasing the thermal poling induced second-order nonlinearity with an ultraviolet laser, to enhance the energy conversion efficiency. The key significance of the proposed THz generation system is the tunability of THz generation in a low cost optical fiber without using a nonlinear crystal. The proposed system was theoretically analyzed and experimentally demonstrated. A tunable THz wave with a frequency from 2.2 to 3.8 THz with an output power of above 0.5 μW was generated.

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