Print ISBN: 978-93-90888-18-4, eBook ISBN: 978-93-90888-26-9

Specialty Optical Fibers for THz Generation: A Review

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DOI: 10.9734/bpi/nupsr/v4/8177D

ABSTRACT

This chapter describes the state-of-the-art sources of terahertz (THz) radiation, with focus on all-optical fiber-based sources for THz generation. THz technology based on the optical fiber platform is expected to be most attractive for day-to-day applications. Though optical fibers have been considered before for low-loss guidance of THz radiation, their nonlinear effects can also be exploited for THz generation. We discuss how a glass-based legacy step index fiber can be used to make a THz source. However, high absorption losses of silica glass in the THz regime and a small overlap between the modes at the optical and THz frequencies limit the THz generation efficiency to a level below 0.01%. Next, we discuss our design of a THz source based on a plastic fiber. By exploiting the nonlinear parametric process of four-wave mixing (FWM) in an appropriately designed microstructured-core double-clad plastic fiber (MC-DCPF), both the loss and the modal overlap issues can be overcome to a great extent. The microstructure geometry of this fiber allows for fine tuning of the required phase matching condition, group-velocity dispersion, and nonlinear properties at the optical pump wavelength. By using such a MC-DCPF, we show that a THz wave at a frequency near 3 THz can be generated by using two commercially available high-power lasers. The high-power CO_2 laser acts as the pump and a CO laser of much lower power acts as a seed for the FWM process. Numerical simulations reveal that more than 30 W of THz power within a bandwidth of 2.13 GHz can be generated at the end of a 65 m long fiber when 1 kW of CO_2 laser power is launched together with 20 W of CO laser power. A conversion efficiency of 30% is possible for a loss-less configuration, but efficiency of > 10% is achievable even in the presence of material losses. Recent results show that further optimization of such plastic microstructured fibers can provide conversion efficiencies close to 45%. As an alternative, we have focused on the use of plastic fibers and discussed a design criterion that is promising for realizing large output powers with a relatively high efficiency.

Keywords: THz source; microstructured optical fiber; plastic fiber; nonlinear optics; four-wave mixing.

1. INTRODUCTION

The frequency range of terahertz (THz) radiation, or T-rays, extends from 0.1 to 10 THz (3 mm to 30 μm) and it bridges the gap (known as the THz gap) between the microwaves and the infrared light [1,2]. Radiation from any object with temperature > 10 K contains THz wavelengths and almost 98% of cosmic background radiation corresponds to THz and far-infrared frequencies [3]. Initially, T-rays were used only for passive applications, where THz radiation was detected to analyze the astronomical objects and to study the chemistry of outer space [3,4]. In recent years, THz technology has experienced significant growth, almost in an exponential manner [5], owing to its potential applications. In the last 20 years, THz-based active applications have emerged, which require a high-

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power THz source, an efficient detection technique, and transmission of THz waves over waveguides. On the one hand, vibrational/rotational transitions of a wide range of molecular clusters and the electronic transitions of various nano-composites exhibit strong resonances at THz frequencies [6,7]. On the other hand, such T-rays penetrate deep inside many materials, such as cloths, papers, wood, ceramics, polymers, walls, dry air etc. These features make THz extremely useful for spectroscopy, sensing, imaging, tomography, medical diagnostics, study of protein dynamics, spintronics, astronomy etc. [1,2,6–10]. Moreover, T-rays do not pass through metals, dust and water, making them popular for security and defense applications [9–11]. This frequency range can transfer huge data files via wireless route and can significantly increase the communication data rate over existing microwave technology [12–14].

Most THz applications require efficient tunable sources emitting broadband THz radiation. Researchers from both optical and electrical disciplines are trying to realize such sources by improving the existing devices as well as developing new ones [5,15–27]. THz waves suffer high metallic losses in conventional electronic circuits designed to operate at frequencies below 100 GHz, and the efficiency and the average output power tend to fall inversely with increasing frequency. Moreover, smaller size of such electronic devices leads to the heating effect [15,28], whose mitigation requires an expensive cryogenic cooling system. In the semiconductor world, THz generation is limited by the lack of suitable narrow-bandgap semiconductors [29–31]. The bandgaps corresponding to THz frequencies (< 10 THz) become comparable to the energy associated with lattice vibrations, resulting in huge thermal noise. Conventional dielectric waveguides such as silica glass fibers are also not useful for guiding THz wave, owing to their high transmission losses [32].

So far, two schemes have been successfully employed for efficient THz generation with high power levels. One of them is based on accelerating charge particles [33], and the other is based on modulation of local polarization [34]. Under the first scheme, reported proposals based on a free-electron laser [33] or synchrotron (or gyrotron) radiation [19,24,35] can generate THz radiation with very high powers (kW to MW level) over a widely tunable range but the required infrastructural facilities are quite expensive for routine use. In the second scheme, laser-induced nonlinear effects have been exploited to generate THz waves both through the resonant and non-resonant processes. Several approaches have been proposed based on a dipole or PC antenna [34,36], optical rectification [17,25], difference-frequency generation in nonlinear crystals [37–39] or polymer materials [20,40], and directly using a quantum cascade laser [22,31,38]. In most cases, the output THz power is quite low (0.01 mW to 10's of mW), though broadband output with a compact design is possible. Other approaches include surface emission in a magnetic field [34], light-induced charge separation in a dielectric [41], and laser-induced plasma [42]. However, the power conversion efficiency remains extremely poor (10^{-4} to10^{-6}) in all cases.

In this chapter, we focus on exploitation of optical techniques for THz technology. More specifically, we concentrate mostly on THz generation based on optical waveguiding. Among different optical waveguides, optical fibers are most attractive for day-to-day applications, and they are emerging as a new platform for THz generation and transmission. In the next section, we discuss how optical fibers made with silica glass and plastics can be employed for efficient THz generation by exploiting the nonlinear optical effects such as four-wave mixing (FWM).

2. THz GENERATION BASED ON OPTICAL FIBERS

Optical fiber technology offers a multitude of applications ranging from high-power laser sources to long-haul data transmission, medical endoscopy, and sensing. For this reason, the use of optical fibers for THz generation has attracted considerable attention. Most of the proposals are based on conventional silica optical fibers [43–45], but the use of plastic fibers has been also proposed [27,46]. In all the cases, nonlinear effects are exploited to generate THz waves with an optical laser source acting as the input pump.

2.1 THz Generation using Conventional Optical Fibers

Conventional optical fibers (fused silica based) exhibit relatively low losses at wavelengths up to about 2 μm, but become highly lossy at longer wavelengths, especially at wavelengths corresponding to

THz frequencies. One sure way to improve the output power of THz radiation generated inside a fiber is to let it radiate out through the side walls of the fiber's core. Such a scheme can be designed by employing the *non-collinear* phase matching. This approach was first proposed by Suizu et al. in [43], when they theoretically investigated the emission of THz waves from the side walls of a silica optical fiber. By using two optical sources, one at a wavelength of ~ 800 nm and other at 1.55 μm, they found that a THz wave can indeed be generated at the frequency of about 2.6 THz. By tuning the pump wavelength between 1.48 and 1.62 μm, the THz frequency could be tuned from 2.52 to 2.64 THz. In Ref. [45], researchers presented detailed derivation of the output THz power using such a configuration. This THz radiation can be collected by wrapping the optical fiber around a bobbin (planar or cylindrical) and then by focusing it through a suitable lens. The total power can be enhanced by using long fiber lengths but the efficiency of this process remains quite low (~ 10^{-6}).

The efficiency of THz generation can be improved somewhat by enhancing the modal overlap between the optical pump and the generated THz wave in a *collinear* phase matching configuration [47]. However, the main drawbacks of this approach are high material losses and a relatively small core size of the fiber. Interestingly, the THz wavelength (<1 mm) is comparable to the size of a fiber's cladding. One solution would be to guide the THz wave through the fiber's cladding [43]. To control the phase-matching condition more precisely, the use of a fiber Bragg grating (FBG) has been proposed [47]. In this scheme, the FBG is designed to introduce proper dispersion for compensating any phase mismatch among the interacting waves. However, the efficiency still remains quite low (~ 10^{-4}). In another configuration, a (100)-oriented InAs thin film was directly attached to one end of a fiber. It was found that a THz wave was emitted from that fiber end when fiber worked as a guiding medium for the optical pump and the THz was actually generated in the InAs film [44]. As the THz is eventually generated from the fiber tip, this scheme could be used for a THz microscopy setup with sub-wavelength spatial resolution of 180 μm.

2.2 THz Generation using Specialty Plastic Fibers

In 2015, we proposed a design for generating high-power THz radiation based on a specialty *plastic* fiber. In this scheme, we exploited nearly degenerate FWM with *collinear* phase matching to generate THz waves [27]. One sure way to increase the efficiency is to improve the modal overlap among the participating waves. In order to achieve this, we consider a microstructured-core double-clad plastic fiber (MC-DCPF). Low-loss plastic, Teflon was chosen to be the fiber base material [48] and commercially available high-power CO_2 and CO lasers emitting near 10.6 μm and 5.59 μm were considered as the pump and the seed light for the FWM process, respectively. Through our simulations, we show that, for a continuous wave (CW) pump of 1 kW power and input seed of ~ 20 W power, CW THz output at 3 THz is achievable in a 65 m long optimized MC-DCPF of our design with a quantum conversion efficiency (η, optical pump-to-THz) of more than three orders of magnitude (η > 0.1) higher than what have been reported to date.

Although several nonlinear processes can be exploited to generate new frequencies [49], FWM is the most relevant process for THz generation in optical fiber, provided the required phase matching condition can be satisfied. In the degenerate FWM process, two pump photons of the same frequency (ω_p) are converted to a signal photon ($\omega_s < \omega_p$) and an idler photon ($\omega_i > \omega_p$), satisfying the energy conservation relation ($2\omega_p = \omega_s + \omega_i$); the subscripts p, s and i stand for pump, signal and idler, respectively. The frequency shift ($\Omega_s = \omega_p - \omega_s$) strongly depends on the group velocity dispersion (GVD) and nonlinear parameters of the fiber at the pump wavelength (λ_p), which should ideally lie close to the designed fiber's zero dispersion wavelength. The FWM efficiency strongly depends on the residual phase mismatch, modal overlap among three waves, effective nonlinearity of the fiber, and fiber's losses [50]. Assuming CW conditions for all the three waves, their evolution in the fiber in terms of their complex amplitudes, $A_j(z)$ (where, j = p, s, i) is governed by the following three coupled equations [50]:

$$\frac{dA_p}{dz} = -\frac{\alpha_p A_p}{2} + \frac{i n_2 \omega_p}{c}\left[\left(f_{pp}\left|A_p\right|^2 + 2\sum_{k=i,s} f_{pk}\left|A_k\right|^2\right)A_p + 2 f_{ppis} A_p^* A_i A_s e^{j\Delta k_L z}\right] \tag{1}$$

$$\frac{dA_i}{dz} = -\frac{\alpha_i A_i}{2} + \frac{i n_2 \omega_i}{c}\left[\left(f_{ii}|A_i|^2 + 2\sum_{k=p,s} f_{ik}|A_k|^2\right)A_i + f_{ispp}A_s^* A_p^2 e^{-j\Delta k_L z}\right] \tag{2}$$

$$\frac{dA_s}{dz} = -\frac{\alpha_s A_s}{2} + \frac{i n_2 \omega_s}{c}\left[\left(f_{ss}|A_s|^2 + 2\sum_{k=p,i} f_{sk}|A_k|^2\right)A_s + f_{sipp}A_i^* A_p^2 e^{-j\Delta k_L z}\right] \tag{3}$$

These equations include pump depletion, losses in the fiber (α_j), and all the necessary Kerr nonlinearity terms. The f_{ij} and f_{ijkl} are modal overlap parameters [49], Δk_L is the linear phase mismatch term (contribution from GVD), which is compensated by self-phase or cross-phase modulation to satisfy the phase matching condition. Considering up to 5th order GVD in our calculation, the Ω_s could be approximated as [50]

$$\Omega_s = \sqrt{\frac{6|\beta_2|}{\beta_4}\left(1 \pm \sqrt{1 - \frac{\beta_4 \gamma P_0}{3\beta_2^2}}\right)} \tag{4}$$

where, β_m is the mth order GVD parameter, γ is the nonlinear parameter and P_0 is the input pump power. For our design task, *multi-order* dispersion management is extremely crucial. Our design target has been to achieve flat dispersion with suitably small values of β_2 and β_4 of opposite signs around λ_p. The parameter n_2 appearing in Eqs. (1) – (3) is expected to vary with the wavelength. For the time being we have assumed its value to be same at the three participating waves. From the literature review it is evident that several polymer materials exhibit high optical Kerr nonlinearity when prepared with proper processing and doping ($n_2 \sim 10^{-18} – 10^{-17}$ m^2/W) [51]. According to Ref. [52], an aqueous suspension of Teflon micro-ellipsoids can acquire exceedingly high value of $n_2 \sim 10^{-14}$ m^2/W, though it may be lower for bulk Teflon. As no universal data for n_2 of bulk Teflon was available in literature at the time of our investigation, we have assumed a nominal value of $n_2 \sim 10^{-17}$ m^2/W (similar to other polymers) for Teflon fiber throughout our numerical analysis.

The primary aim is to improve the modal overlap among the input optical (pump and idler) and generated THz waves, along with a proper dispersion profile at λ_p in order to achieve efficient generation of THz waves. However, the fiber should be effectively single-moded with a low loss. Since wavelengths of different waves involved in the parametric process are very different, it is a challenge to satisfy all the aforementioned criteria simultaneously. We balanced them by choosing optimal fiber parameters of our proposed double clad fiber design. For the fiber structure, we consider three kinds of Teflon materials with slightly different refractive indices. These are easily available in the market as different commercial suppliers can provide Teflon with different refractive indices [48]. As a first step in design recipe, we considered a microstructured-core based *large mode area* fiber (similar to that reported in [53]) to realize an ultra-high effective mode area (A_{eff}) at λ_p and λ_i; a schematic cross-sectional view of the microstructured-core fiber is shown in Fig. 1(a). The microstructured-core is formed by using 4 rings of hexagonally arranged higher index rods (n_r = 1.44, Teflon-type-1 shown as white circles in Fig. 1(a)) embedded in a lower index background ($n_b \sim$ 1.425, Teflon-type-2, dark blue in color), which also forms the uniform cladding (1st cladding) for λ_p and λ_i. The radius of high index rods and pitch in the microstructured-core are denoted by r and Λ, respectively, which were optimized to 1 μm and 30 μm, respectively for achieving effective single-mode operation with low confinement loss (α_c) over the targeted spectral range. Though the microstructured-core fiber is multimoded, the value of α_c for higher-order modes is more than 5 orders of magnitudes higher, and hence these modes leak away rapidly after a short length of propagation. For THz wave (λ_s ~ 100 μm), this structure, as a whole, (Fig. 1(a)) acts as the fiber core with refractive index equivalent to the average index of that region (n_{av}, light purple color in Fig. 1(b)). Now by adding another cladding (2nd clad of refractive index, n_{cl} = 1.4, Teflon-type-3, light blue color in Fig. 1(b)) around this equivalent core, we can define an equivalent step-index fiber (E-SIF) structure for THz wave (cf. Fig. 1(b)). For this E-SIF structure, the core radius (R_1) is optimized to 150 μm by limiting the fiber V number to near about 2.4 [54], so that single-mode operation can be established for THz wave also. The outer boundary of this cladding (radius R_2) is fixed to get negligible α_c at the THz wavelength. Combining these two structures, we propose a MC-DCPF geometry (cf. Fig. 1(c)), where modal overlap between the three waves can be up to ~ 70%. The GVD parameters as well as the modal fields were calculated with the open access software CUDOS, and Eqs. (1) to (3) were solved numerically in MATLAB®.

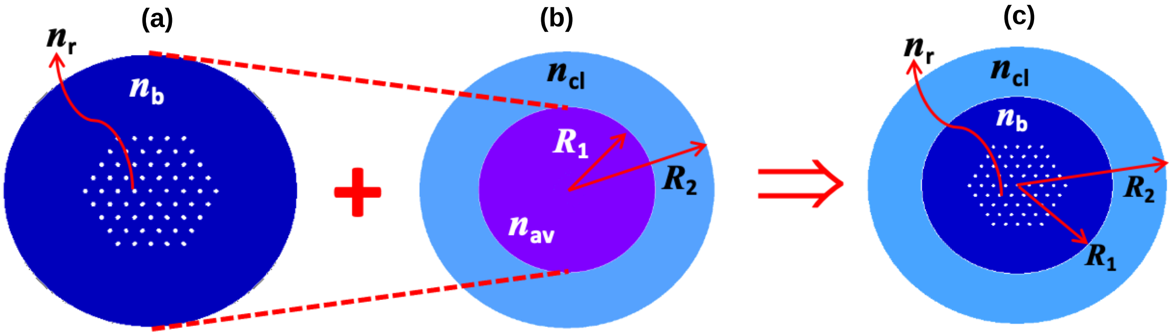

Fig. 1. [Adapted] with permission from [27] © The Optical Society. (a) Effective cross-section of the designed fiber for optical waves. The core is formed by hexagonally arranged 4 rings of high index rods of radius = 1 µm (white circles) and of pitch = 30 µm in a uniform lower index background of much wider cross-section (dark blue color), which effectively forms the cladding; (b) Effective cross-section for the THz wave, where core of radius R_1 is formed by an average index (n_{av}, light purple color) with uniform cladding (2nd clad, shown in light blue color); (c) The combined cross-section of the proposed MC-DCPF

We have considered the commercially available high power CO_2 laser as pump (λ_p ~ 10.6 µm) and commercially available CO laser (~ 5.6 µm) as idler, which can be used as input in order to realize THz output at ~ 3 THz (λ_s ~ 100 µm). It is important to mention that, launching of a weak idler along with the pump improves the FWM efficiency considerably as it stimulates the FWM process. We have studied the modal properties of the three waves and investigated their dispersion behavior around λ_p in order to find the GVD parameters. Since the effective contribution (in terms of weighted percentage) of the region with index n_b is much larger than the other regions (indices n_r and n_{cl}), we have employed a proper material dispersion model for n_b but used fixed values for n_r and n_{cl}. The variation of β_2 and β_4 with wavelength for the optimum fiber structure is shown in Figs. 2(a) and 2(b), respectively. The optimum values of β_2 and β_4 are found to be -8.94 ps^2/km and 4.23 × 10^{-3} ps^4/km, respectively at λ_p = 10.58 µm. For an input pump power (P_0) of 1 kW and seed power of 20 W, the THz wave is generated centered at 99.45 µm (≈ 3.0145 THz).

The evolution of three waves along the propagation direction is studied by numerically solving Eqs. (1) – (3). The amplification factor (*AF*) is defined as the ratio of output and input power, such that, AF_j = $P_{j,out}/P_{i,in}$ for j = i, s and $P_{j,out}/P_0$ for j = p, where, $P_{j,out}$ is the output power and $P_{i,in}$ is the input idler/seed power. Changes in *AF* for these three waves along fiber length (*L*) are plotted in Fig. 3(a) for a $P_{i,in}$ = 20 W. Power variations are plotted in Fig. 3(b). Both figures reveal that the maximum power transfer from pump to generated THz wave takes place at *L* = 64.7 m. It is worthwhile to mention that, for the proposed MC-DCPF, A_{eff} at the pump and generated THz waves are extremely large (~ 36,000 µm² and 78,000 µm², respectively). As a result, though we have assumed a relatively high power at the input, the effective intensity was only ~ 0.003 GW/cm^2, which is much lower than the potential onset of other resonance based nonlinear effects.

Even after including pump depletion, THz power of > 30 W is achievable (cf. Fig. 3(b)) with a quantum conversion efficiency from optical pump-to-THz, $\eta = \left(P_{s,out}\lambda_s / P_0\lambda_p\right) > 0.3$, which was the highest value reported at the then 2015 publication. We have also investigated the effect of *seeding* on the amplification factor and found that, it essentially dictates the optimum fiber length (L_{opt}). The variation of L_{opt} with $P_{i.in}$ is plotted in Fig. 4(a), where we see an inverse relationship between the two. We may mention that L_{opt} can be further reduced by increasing the effective nonlinearity, $\gamma = \left(2\pi n_2 / \lambda A_{eff}\right)$ of the medium. The phase matching bandwidth of the generated THz signal is investigated by studying the variations of $P_{s,out}$ around the generated T-ray (3.015 THz) (shown in Fig. 4(b)), where the 3-dB bandwidth is ~ 2.13 GHz (≈ 70 nm). Further by tuning the λ_p, generated λ_s can be tuned.

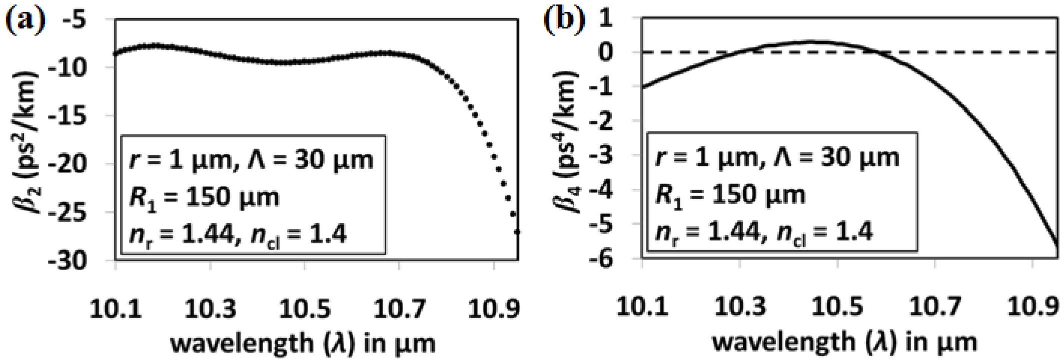

Fig. 2. [Reprinted] with permission from [27] © The Optical Society. Variation of (a) β_2 and (b) β_4 with the operating wavelength around pump wavelength for optimum fiber parameters

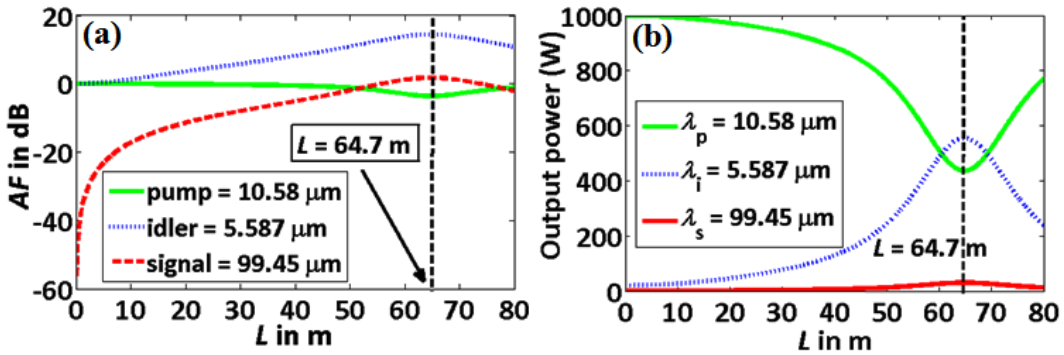

Fig. 3. [Reprinted] with permission from [27] © The Optical Society. Variation of (a) amplification factor (*AF*) and (b) output power along fiber length (*L*) for λ_P = 10.58 μm (green color), λ_s = 99.45 μm (red color) and λ_i = 5.587 μm (blue color)

Variation of the pointing vector (S_z) along the *x* direction (fiber cross-section) is plotted for both the pump and THz wave as shown in Fig. 5(a). This shows the confinement of THz frequency is lower than the pump, as expected, however, we have been able to make them reasonably similar. The preceding results neglected fiber losses. We briefly discuss the impact of material loss of Teflon. According to the commercial datasheet [48], Teflon with quite good transmission at all the three wavelengths of interest can be fabricated. After inclusion of the loss (0.01 m^{-1}), η becomes 0.1. Although smaller by a factor 3 compared to the loss-free case, it is still 2 - 3 orders of magnitude higher than the previously reported results in the literature. The length of our proposed fiber is relatively long. To make a compact device, fiber can be wrapped around a circular mandrel/bobbin. However, this may lead to intolerable bend-loss (a_b). Keeping this in mind, we have studied a_b of the proposed MC-DCPF at THz wavelength by considering effective step-index fiber approximation and using the following formula for pure bend-loss [54]:

$$a_b = \frac{1}{8}\sqrt{\frac{p}{R_1 R_b W^3}} S(V,W)\cdot \exp\left(- \frac{4R_b W^3 \Delta}{3V^2 R_1} \right) \tag{5}$$

where,

$$S(V,W) = \frac{R_1^2}{K_0^2(W)}\left[\int_0^\infty \frac{E^2(r)}{E^2(R_1)} r\,dr\right]^{-1} \tag{6}$$

R_1 is the core radius, R_b is the bend radius, V, W and Δ are the conventional fiber waveguide parameters as described in [54] and the function $S(V,W)$ can be calculated from modal field distribution $E(r)$ and K_0 is the zero[th] order modified Bessel function. The variation of a_b with R_b for the proposed MC-DCPF is plotted in Fig. 5(b). Estimated bending loss is reasonably low for the proposed fiber structure. More specifically, it becomes negligible for $R_b \geq 10$ cm, which is quite favorable for our targeted design.

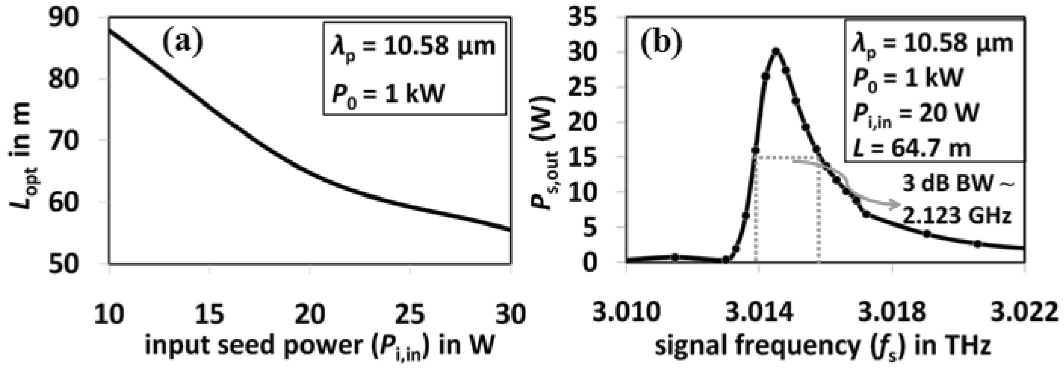

Fig. 4. [Reprinted] with permission from [27] © The Optical Society. (a) Variation of optimum fiber length (L_{opt}) with input seed idler power for a fixed pump power of 1 kW. (b) Output spectrum of generated THz wave; 3-dB phase matching bandwidth is ~ 2.13 GHz (≈ 70 nm)

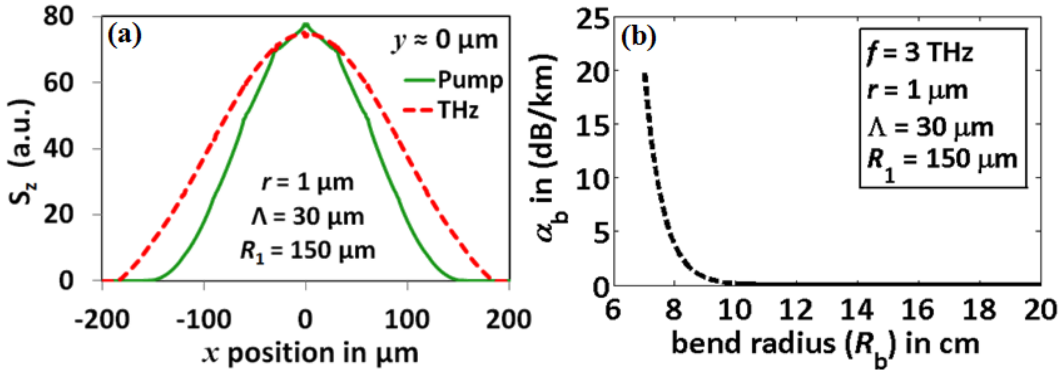

Fig. 5. [Reprinted] with permission from [27] © The Optical Society. (a) 1-dimentional variation of pointing vector (S_z) for pump and THz wave. (b) Variation of bending loss (a_b) as a function of bend radius (R_b) of the proposed MC-DCPF at ~ 3 THz

In recent years, researchers have tried to further efficiency scaling of plastic fiber-based THz generation [46] by mainly improving the fiber design. The authors have theoretically shown THz wave generation at 9.33 THz from a CO_2 laser as pump and CO laser as seed idler within 7 m long plastic fiber. The estimated quantum efficiency is ~ 0.46, which is 1.5-times improvement compared to the previous publication [27].

3. CONCLUSION

In this chapter we focused on THz wave generation using optical methods and exploring versatile optical fiber technology. Though several proposals for THz generation based on conventional silica fibers exist in the literature, their conversion efficiency is limited to below 0.01%. As an alternative, we have focused on the use of plastic fibers and discussed a design criteria that is promising for realizing large output powers with a relatively high efficiency.

We have discussed in detail the theoretical design of efficient fiber-based THz source by exploiting degenerate four-wave mixing process in a Teflon-based novel microstructured-core double-clad plastic fiber (MC-DCPF). The aim of this research is to employ commercially available high power mid-infrared light sources as the pump and seed idler in order to generate THz radiation via nonlinear four-wave mixing process. The collinear phase matching condition is achieved by tailoring the design of the MC-DCPF with proper dispersion and nonlinearity around the pump wavelength. The efficiency of nonlinear process is improved by maximizing the modal overlaps among all the three waves; overlap > 70% is achieved for optical and THz waves. This is the most difficult but crucial step in the targeted fiber design. Effective single-mode operation is ensured throughout. For a pump of 1 kW power emitting at 10.58 μm, a THz wave centered at 3 THz could be generated with ~ 30 W of CW power at the output end of a 64.7 m long designed fiber. Including pump depletion and material loss, the optical to THz quantum conversion efficiency ~ 10% should be realizable, which is ~ 2 - 3 orders of magnitude higher than previously reported results. The 3-dB phase matching bandwidth of the generated THz wave is about 70 nm (~ 2.13 GHz). The relatively long fiber length would not be an issue since such a plastic fiber can be spooled in a circular mandrel/bobbin to make it compact for convenient handling; bend-induced loss is negligible for bend radii ≥ 10 cm, which is two orders of magnitude lower than a typical synchrotron setup for THz generation [35]. The proposal should serve as the initial design platform to fabricate efficient fiber-based THz sources. Further research with new design for improved efficiency is emerging. The microstructured geometry is relatively simple, and should be realizable in practice as it is amenable to well-matured state-of-the-art fabrication technologies [55,56].

DISCLAIMER

The book chapter is based on the following peer-reviewed published article:

Ajanta Barh, R. K. Varshney, G. P. Agrawal, B. M. A. Rahman, and B. P. Pal, "Plastic fiber design for THz generation through wavelength translation," Opt. Lett. 40, 2107-2110 (2015).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Zhang X-C. Terahertz wave imaging: Horizons and hurdles. Phys. Med. Biol. 2002;47:3667–3677.
2. Abbott D, Zhang X. Special issue on T-ray imaging, sensing and retection. Proc. IEEE. 2007;95:1509–1513.
3. Siegel PH. THz for space: The golden age. In 2010 IEEE MTT-S International Microwave Symposium. 2010;1–1.
4. Kulesa C. Terahertz spectroscopy for astronomy: From comets to cosmology. IEEE Trans. Terahertz Sci. Technol. 2011;1:232–240.
5. Lewis RA. A review of terahertz sources. J. Phys. Appl. Phys. 2014;47:374001.
6. Theuer M, Harsha SS, Molter D, Torosyan G, Beigang R. Terahertz time-domain spectroscopy of gases, liquids and solids. ChemPhysChem. 2011;12:2695–2705.
7. Zhan H, Wu S, Bao R, Ge L, Zhao K. Qualitative identification of crude oils from different oil fields using terahertz time-domain spectroscopy. Fuel. 2015;143:189–193.
8. Guillet JP, Recur B, Frederique L, Bousquet B, Canioni L, Manek-Hönninger I, Desbarats P, Mounaix P. Review of Terahertz tomography techniques. J. Infrared Millim. Terahertz Waves. 2014;35:382–411.
9. Davies AG, Burnett AD, Fan W, Linfield EH, Cunningham JE. Terahertz spectroscopy of explosives and drugs. Mater. Today. 2008;11:18–26.

10. Tao YH, Fitzgerald AJ, Wallace VP. Non-contact, non-destructive testing in various industrial sectors with Terahertz technology. Sensors. 2020;20:712.
11. Akmalov AE, Aksenov EA, Kotkovskii GE, Kozlovskii KI, Maksimov EM, Plekhanov AA, Chistyakov AA. Spectral identification of traces of explosives in reflected terahertz radiation. In Counterterrorism, Crime Fighting, Forensics, and Surveillance Technologies III (International Society for Optics and Photonics). 2019;11166:111660A.
12. Song H, Nagatsuma T. Present and future of Terahertz communications. IEEE Trans. Terahertz Sci. Technol. 2011;1:256–263.
13. Nagatsuma T, Ducournau G, Renaud CC. Advances in terahertz communications accelerated by photonics. Nat. Photonics. 2016;10:371–379.
14. Chen Z, Ma X, Zhang B, Zhang Y, Niu Z, Kuang N, Chen W, Li L, Li S. A survey on terahertz communications. China Commun. 2019;16:1–35.
15. Samoska LA. An overview of solid-state integrated circuit amplifiers in the submillimeter-wave and THz regime. IEEE Trans. Terahertz Sci. Technol. 2011;1:9–24.
16. Acharyya A. 1.0–10.0 THz radiation from graphene nanoribbon based avalanche transit time sources. Phys. Status Solidi A. 2019;216:1800730.
17. Xu S, Liu J, Zheng G, Li J. Broadband terahertz generation through intracavity nonlinear optical rectification. Opt. Express. 2010;18:22625–22630.
18. Delfanazari K, Klemm RA, Tsujimoto M, Cerkoney DP, Yamamoto T, Kashiwagi T, Kadowaki K. Cavity modes in broadly tunable superconducting coherent terahertz sources. J. Phys. Conf. Ser. 2019;1182:012011.
19. Glyavin MY, Idehara T, Sabchevski SP. Development of THz gyrotrons at IAP RAS and FIR UF and their applications in physical research and high-power THz technologies. IEEE Trans. Terahertz Sci. Technol. 2015;5:788–797.
20. Rahman A, Rahman AK, Tomalia DA. Engineering dendrimers to produce dendrimer dipole excitation based terahertz radiation sources suitable for spectrometry, molecular and biomedical imaging. Nanoscale Horiz. 2017;2:127–134.
21. Fülöp JA, Tzortzakis S, Kampfrath T. Laser-driven strong-field terahertz sources. Adv. Opt. Mater. 2020;8:1900681.
22. Li LH, Chen L, Freeman JR, Salih M, Dean P, Davies AG, Linfield EH. Multi-Watt high-power THz frequency quantum cascade lasers. Electron. Lett. 2017;53:799–800.
23. Lee AJ, Spence DJ, Pask HM. Terahertz sources based on stimulated polariton scattering. Prog. Quantum Electron. 2020;71:100254.
24. Evain C, Szwaj C, Roussel E, Rodriguez J, Le Parquier M, Tordeux M-A, Ribeiro F, Labat M, Hubert N, Brubach J-B, Roy P, Bielawski S. Stable coherent terahertz synchrotron radiation from controlled relativistic electron bunches. Nat. Phys. 2019;15:635–639.
25. Xu J, Globisch B, Hofer C, Lilienfein N, Butler T, Karpowicz N, Pupeza I. Three-octave terahertz pulses from optical rectification of 20 fs, 1 $\upmu$m, 78 MHz pulses in GaP. J. Phys. B At. Mol. Opt. Phys. 2018;51:154002.
26. Cao Y, YE, Huang P, Zhang X-C. Broadband terahertz wave emission from liquid metal. Appl. Phys. Lett. 2020;117:041107.
27. Barh A, Varshney RK, Agrawal GP, Rahman BMA, Pal BP. Plastic fiber design for THz generation through wavelength translation. Opt. Lett. 2015;40:2107–2110.
28. Armstrong CM. The truth about terahertz. IEEE Spectr. 2012;49:36–41.
29. Mullins J. Using unusable frequencies [solid-state terahertz laser]. IEEE Spectr. 2002;39:22–23.
30. Fülöp JA, Polónyi G, Monoszlai B, Andriukaitis G, Balciunas T, Pugzlys A, Arthur G, Baltuska A, Hebling J. Highly efficient scalable monolithic semiconductor terahertz pulse source. Optica. 2016;3:1075–1078.
31. Bosco L, Franckié M, Scalari G, Beck M, Wacker A, Faist J. Thermoelectrically cooled THz quantum cascade laser operating up to 210 K. Appl. Phys. Lett. 2019;115:010601.
32. Barh A, Pal BP, Agrawal GP, Varshney RK, Rahman BMA. Specialty fibers for terahertz generation and transmission: A review. IEEE J. Sel. Top. Quantum Electron. 2016;22:365–379.
33. Williams GP. Filling the THz gap—high power sources and applications. Rep. Prog. Phys. 2005;69:301–326.
34. Kitaeva GK. Terahertz generation by means of optical lasers. Laser Phys. Lett. 2008;5:559–576.

35. Wang F, Cheever D, Farkhondeh M, Franklin W, Ihloff E, van der Laan J, McAllister B, Milner R, Tschalaer C, Wang D, Wang DF, Zolfaghari A, Zwart T, Carr GL, Podobedov B, Sannibale F. Coherent THz synchrotron radiation from a storage ring with high-frequency RF system. Phys. Rev. Lett. 2006;96:064801.
36. Burford NM, El-Shenawee MO. Review of terahertz photoconductive antenna technology. Opt. Eng. 2017;56:010901.
37. Ding YJ. Progress in terahertz sources based on difference-frequency generation [Invited]. JOSA B. 2014;31:2696–2711.
38. Belkin MA, Capasso F, Belyanin A, Sivco DL, Cho AY, Oakley DC, Vineis CJ, Turner GW. Terahertz quantum-cascade-laser source based on intracavity difference-frequency generation. Nat. Photonics. 2007;1:288–292.
39. Ragam SR, Zhao P, Oyama Y. Chapter 2 - Terahertz sources based on difference-frequency generation for spectroscopy and biomaterial analysis. In Terahertz Biomedical and Healthcare Technologies, A. Banerjee, B. Chakraborty, H. Inokawa, and J. Nath Roy, Eds. (Elsevier). 2020;43–55.
40. Rahman A. Dendrimer based terahertz time-domain spectroscopy and applications in molecular characterization. J. Mol. Struct. 2011;1006:59–65.
41. Optically-induced charge separation and terahertz emission in unbiased dielectrics. Journal of Applied Physics. Vol 109, No 6.
Available:https://aip.scitation.org/doi/full/10.1063/1.3561505?casa_token=Rrzr4i4isIQAAAAA%3AAm93pxSpwN4GxY0D3nwq2lspRQ9-FQWPC3l8e3uKa_DvkHBaUuqZ_C9CUnTsCgv9OWAb549eEP0
42. Liao G, Li Y. Review of intense terahertz radiation from relativistic laser-produced plasmas. IEEE Trans. Plasma Sci. 2019;47:3002–3008.
43. Suizu K, Kawase K. Terahertz-wave generation in a conventional optical fiber. Opt. Lett. 2007;32:2990–2992.
44. Yi M, Lee K, Lim J, Hong Y, Jho Y-D, Ahn J. Terahertz waves emitted from an optical fiber. Opt. Express. 2010;18:13693–13699.
45. Zhou P, Fan D. Terahertz-wave generation by surface-emitted four-wave mixing in optical fiber. Chin. Opt. Lett. 2011;9:051902.
46. Kumar V, Varshney RK, Kumar S. Terahertz generation by four-wave mixing and guidance in diatomic teflon photonic crystal fibers. Opt. Commun. 2020;454:124460.
47. Qasymeh M. Terahertz generation in an electrically biased optical fiber: A theoretical investigation.
Available:https://www.hindawi.com/journals/ijo/2012/486849/
48. TYDEX THz materials.
Available:http://www.tydexoptics.com/products/thz_optics/thz_materials/
49. Agrawal GP. Nonlinear Fiber Optics, 4th Ed. (Elsevier); 2006.
50. Barh A, Ghosh S, Varshney RK, Pal BP. An efficient broad-band mid-wave IR fiber optic light source: Design and performance simulation. Opt. Express. 2013;21:9547–9555.
51. Kaino T, Katayama Y. Polymers for optoelectronics. Polym. Eng. Sci. 1989;29:1209–1214.
52. Pizzoferrato R, Marinelli M, Zammit U, Scudieri F, Martellucci S, Romagnoli M. Optically induced reorientational birefringence in an artificial anisotropic Kerr medium. Opt. Commun. 1988;68:231–234.
53. Barh A, Ghosh S, Varshney RK, Pal BP. Ultra-large mode area microstructured core chalcogenide fiber design for Mid-IR beam delivery. Opt. Commun. 2013;311:129–133.
54. Neumann E-G. Single-Mode Fibers: Fundamentals (Springer); 2013.
55. Arrospide E, Durana G, Azkune M, Aldabaldetreku G, Bikandi I, Ruiz-Rubio L, Zubia J. Polymers beyond standard optical fibres – fabrication of microstructured polymer optical fibres. Polym. Int. 2018;67:1155–1163.
56. Argyros A. Microstructured polymer optical fibers. J. Light. Technol. 2009;27:1571–1579.

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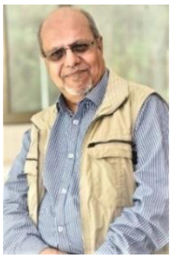

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This chapter is an extended version of the article published by the same author(s) in the following journal.
Optics Letters (OSA Publishing), 40(9): 2107-2110, 2015.