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Terahertz Generation and Detection Using Frequency Conversion

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Abstract: Terahertz is nonlinearly upconverted to telecommunication wavelengths, resulting in detection with 4.5 pW/Hz$^{1/2}$ noise equivalent power and nanosecond temporal resolution. Optical frequencies from an ultrashort pulse mix, generating 3 mW of broadband terahertz.

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Component technology in the near infrared is much more advanced than that in the terahertz or far infrared. More specifically, detectors at telecommunication wavelengths can count single photons at gigahertz bandwidths. Near infrared sources such as ti-sapphire and erbium doped amplifiers can emit a few watts of power. So, researchers have sought to leverage the more mature optical components to improve terahertz technology. Terahertz radiation can be mixed in a nonlinear $\chi(2)$ crystal with 1 μm [2-4] and 1.5 μm [5] optical pumps to generate optical sidebands. These upconverted terahertz signals, or idler photons, can then be detected with conventional optical receivers. Likewise, also from a $\chi(2)$ process, terahertz sources can be synthesized by beating two optical frequencies (eg, [2, 3, 6-10]). The resulting terahertz frequency is a difference of the two optical pump frequencies.

This paper is composed of two parts. First, we review our terahertz receiver based on frequency upconversion. Using 1550 nm pump and a photon-counting detector, this receiver has a terahertz noise equivalent power (NEP) of 4.5 pW/$\sqrt{\text{Hz}}$ and temporal resolution of 1 ns [5]. Secondly, we will report on a terahertz source using optical rectification, where different optical frequency components within a single ultrashort pulse mix generating terahertz [6]. This technique has generated 3 mW of broadband terahertz [8].

The terahertz receiver is based on frequency upconversion of the terahertz signal by a near infrared pump. The optical pump consists of 10 ns pulses separated by 5 μs, and is 0.2 nm wide centered at 1550 nm. An erbium doped fiber amplifier boosts the average power to 630 mW and the peak power to 315 W [5]. The terahertz waves come from a backward wave oscillator that emits 2.5 mW at 700 GHz. The 1550 nm pump and 700 GHz radiation are focused on a 4 mm long GaAs crystal. GaAs was chosen for its low material absorption and high $\chi(2)$ nonlinearity. This crystal's nonlinear mixing of the pump pulses and CW terahertz generates idler pulses centered about 1555.6 nm. This conversion setup is described in more detail in [5].

The residual THz beam is rapidly expanding and is not collected by the optics. The idler, however, is coupled with lenses and a collimator into regular single mode fiber. Once coupled to fiber, the idler goes to a switch/attenuator followed by a Princeton Lightwave Geiger Mode avalanche photodiode (GM-APD). This receiver was set with a 1 ns wide gate, which means we could resolve terahertz pulses with nanosecond widths or gigahertz electrical bandwidths. The GM-APD is attached to a counter, which records the number of gates with photons within a one second interval. Its optical NEP is $9.3 \cdot 10^{-17}$ W/$\sqrt{\text{Hz}}$ at the idler wavelength.

Figure 1 plots GM-APD's detected counts (within one second interval) versus terahertz power. Since calibrated, large dynamic range terahertz attenuators are hard to find, we use an optical attenuator to reduce the idler power and thus simulate a terahertz attenuator. This signal line intersects with the measured noise, or dark count fluctuations, at $4.5 \cdot 10^{-12}$ W/$\sqrt{\text{Hz}}$, giving the terahertz NEP value. Since the GM-APD has a 1 ns gate, it means we can detect a terahertz pulse energy of only $3.2 \cdot 10^{-19}$ J, which is orders of magnitude lower than any bolometer. Of course, over a second, there would be 200,000 of these pulses. Taking the ratio of the optical NEP to the terahertz NEP gives a system power conversion efficiency of $2.1 \cdot 10^{-5}$ or a photon conversion efficiency of $7.6 \cdot 10^{-8}$. The intrinsic photon conversion efficiency in the crystal is higher. To convert between the two, one needs to take into account the 3 dB from the three pump blocking filters, 2 dB from Fresnel loss as idler exits crystal, 2 dB from Fresnel as the terahertz enters crystal, and 7 dB from fiber coupling loss. Improving conversion efficiency and increasing pump power will be focus of future work.

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The terahertz source relies on a frequency down conversion process commonly called optical rectification. The pump laser is a 100 fs, regeneratively amplified ti-sapphire oscillator. Since 100 fs pulses have a couple terahertz of optical linewidth, the “red” and the “blue” frequency components of the same optical pulse mix in a $\chi(2)$ crystal to generate terahertz. Although this has been demonstrated early on in lithium niobate [6], the powers generated with this collinear technique have been relatively modest. Recently researchers have used a diffraction grating to disperse different frequencies into different angles and added a focusing lens to reimage the light onto the crystal. Because the “red” and “blue” components are at different angles, the intensity front of the light at the crystal is sharply tilted, resulting in greatly enhanced velocity matching [7]. This pump tilting leads to improved conversion efficiency and increased terahertz power. The generated terahertz exits at a large angle from the optical pump light direction.

Here, a 6 mJ pulse at 1 kHz repetition rate was tilted and focused on a 0.6% MgO-doped stoichiometric lithium niobate crystal at room temperature. Details of the setup can be found in reference [8]. The spectrum of the generated terahertz can be found in figure 2. Most of the energy falls between 0.5 to 2.5 THz. Electro-optic sampling with a 1 mm ZnTe crystal measures the terahertz pulse to be 1 ps wide. The pump-to-terahertz energy conversion efficiency is $7\cdot10^{-4}$ so the average terahertz power is 3 mW. To our knowledge, this is the highest reported terahertz power generated by any frequency conversion method.

Nonlinear $\chi(2)$ crystals can also be used to generate narrow band but tunable terahertz radiation as shown by many groups (for example, see [2, 3, 9, 10]). Other groups have used GaAs as $\chi(2)$ crystal [9] and 1550 nm as pumps [10], but here we combine both approaches and mix in GaAs optical pulses centered about 1550 and 1558 nm. Both wavelengths are amplified by a single erbium doped fiber amplifier. The average power is 3 W and the peak power is 1.5 kW. The terahertz power from this “first light” measurement is about 5 nW average power.

In conclusion, we demonstrated very sensitive and fast terahertz detection using frequency upconversion with relatively modest 1550 nm pumps. We have also shown that we can generate terahertz using GaAs and erbium doped fiber amplifiers. Using more powerful amplifiers and noncollinear optical rectification, we have generated 3 mW of broadband terahertz with an energy conversion efficiency of $7\cdot10^{-4}$.

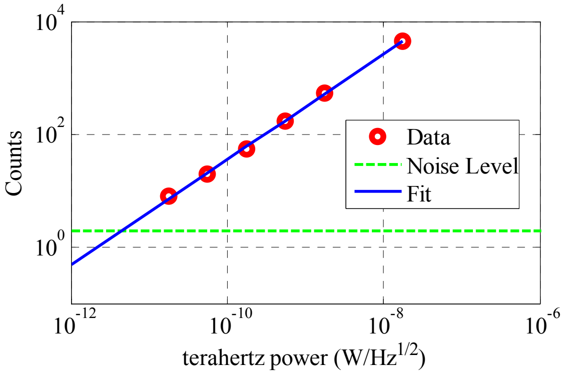

Fig. 1: Counts from Geiger mode APD versus terahertz power.

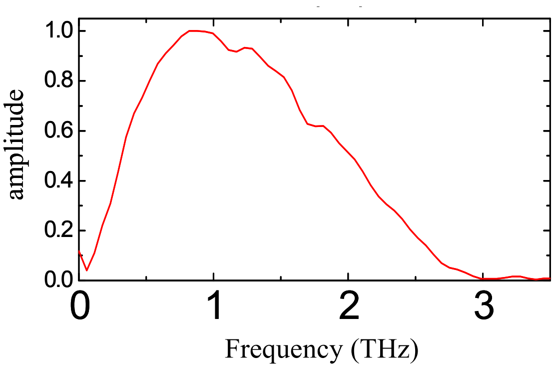

Fig. 2: Terahertz spectrum generated by optical rectification.

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