2009

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Publication Details

This article was originally published as Horvat, J and Lewis, RA, Peeling adhesive tape emits electromagnetic radiation at terahertz frequencies, Optics Letters, 34(14), 2009, 2195-2197.

Peeling adhesive tape emits electromagnetic radiation at terahertz frequencies

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Received April 14, 2009; revised June 12, 2009; accepted June 16, 2009;
posted June 18, 2009 (Doc. ID 110103); published July 13, 2009

An unusual concept for a simple and inexpensive terahertz source is presented: unpeeling adhesive tape. The observed spectrum of this terahertz radiation exhibits a peak at 2 THz and a broader peak at 18 THz. The radiation is not polarized. The mechanism of terahertz radiation is tribocharging of the adhesive tape and subsequent discharge, possibly bremsstrahlung with absorption or energy density focusing during the dielectric breakdown of a gas. The accompanying optical emission is also a consequence of tribocharging.

OCIS codes: 000.2170, 000.2190, 000.3110, 230.6080, 300.6495, 350.5610.

The terahertz (THz, 10^{12} Hz) region of the electromagnetic spectrum, which may be taken to span 0.1 to 10 THz, lies between the IR and microwave and promises wide application across biology, chemistry, physics, and medicine [1–3]. Existing THz sources suffer limitations: thermal radiators are weak, free-electron lasers and time-domain spectrometers are cumbersome, and quantum-cascade lasers require cooling [4,5]. New mechanisms of THz generation merit investigation to bridge the so-called THz gap presently separating electronics and photonics. Here we show that peeling adhesive tape emits THz radiation. The emission of visible light, radio frequency waves, and x rays from peeling adhesive tape has been previously reported [6–10].

Peeling adhesive tape produces x-ray emission [7] strong enough for x-ray imaging [10]. This was explained by the tribocharging mechanism [8]. On peeling, the adhesive side becomes positively charged, and the tape below negatively charged. The build-up of an electric field results in a discharge, accelerating the charges. In vacuum, the charges may gain enough energy to produce x rays via bremsstrahlung. We extend this to suggest that THz-frequency radiation will also arise. The rapid recombination of charge may induce transient currents with THz-frequency components. In contrast to the x-ray process, vacuum is not essential. Through a series of experiments, we have now confirmed this proposed emission of THz radiation from peeling tape.

We measured the radiation emitted by peeling adhesive tapes using the apparatus in Fig. 1. All measurements were at ambient pressure and temperature. The tape was fed from one spool to another, as described earlier [10]. Both spools ran on ball bearings. A variable-speed motor could engage the drive spool. An optical encoder monitored rotation. The detectors were liquid He-cooled 4.2 K Si bolometers of sensitivity 2×10^5 V/W. The radiation was optically chopped at 181 Hz and fed to an SRS830 lock-in amplifier. A GW1002 digital storage oscilloscope recorded the data.

Figure 2(a) shows a typical signal as the adhesive tape was unwound. The optical filters ensured that only radiation of 0.1–3 THz was detected. As the motor drive was engaged [at ~8 s in Fig. 2(a)], the THz signal increased abruptly above the background. We conclude that the peeling tape emits THz radiation.

We investigated the effect of the tape speed on the THz emission. There was a regularity in the THz signal in phase with the spool rotation, more evident at lower speeds and attributed to the ellipticity of the tape spool. (The same oscillation is observed in the visible emission.) The amplitude of the initial rise of THz signal did not depend strongly on the drive speed. After the initial rise, there was often a slower additional small increase in THz signal [~8 to ~18 s in Fig. 2(a)]. This was slightly greater for higher drive speeds. The signal abruptly decreased when the motor drive was disengaged [~18 s in Fig. 2(a)], followed by a more gradual decrease to the background level. These features were observed over many repeated runs.

The intensity of THz radiation slightly decreased with repeated peeling of the tape. We have rewound the tape up to five times and still obtained strong

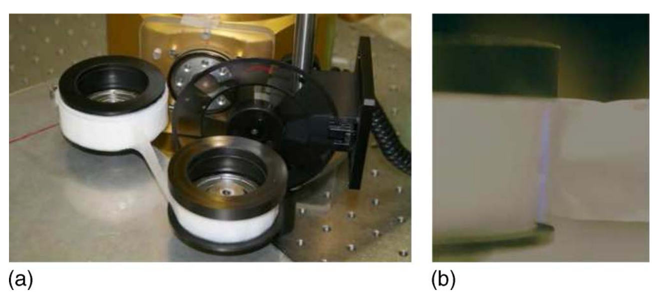

Fig. 1. (Color online) Apparatus for investigating terahertz emission from peeling adhesive tape. (a) Tape unwinds from the spool in the right foreground to the other spool. Radiation from the peeling vertex traverses a rotating optical chopper before entering the detector cryostat through a semitransparent white polyethylene vacuum window. A Winston cone concentrates the radiation onto the silicon bolometer element. (b) Glow of bluish light as the tape unwinds. Two images are superposed: one in daylight for stationary tape, the other in darkness for unwinding tape. The exposure time for the glow was 20 s, lens aperture $f/2.8$, and sensor sensitivity ISO1600.

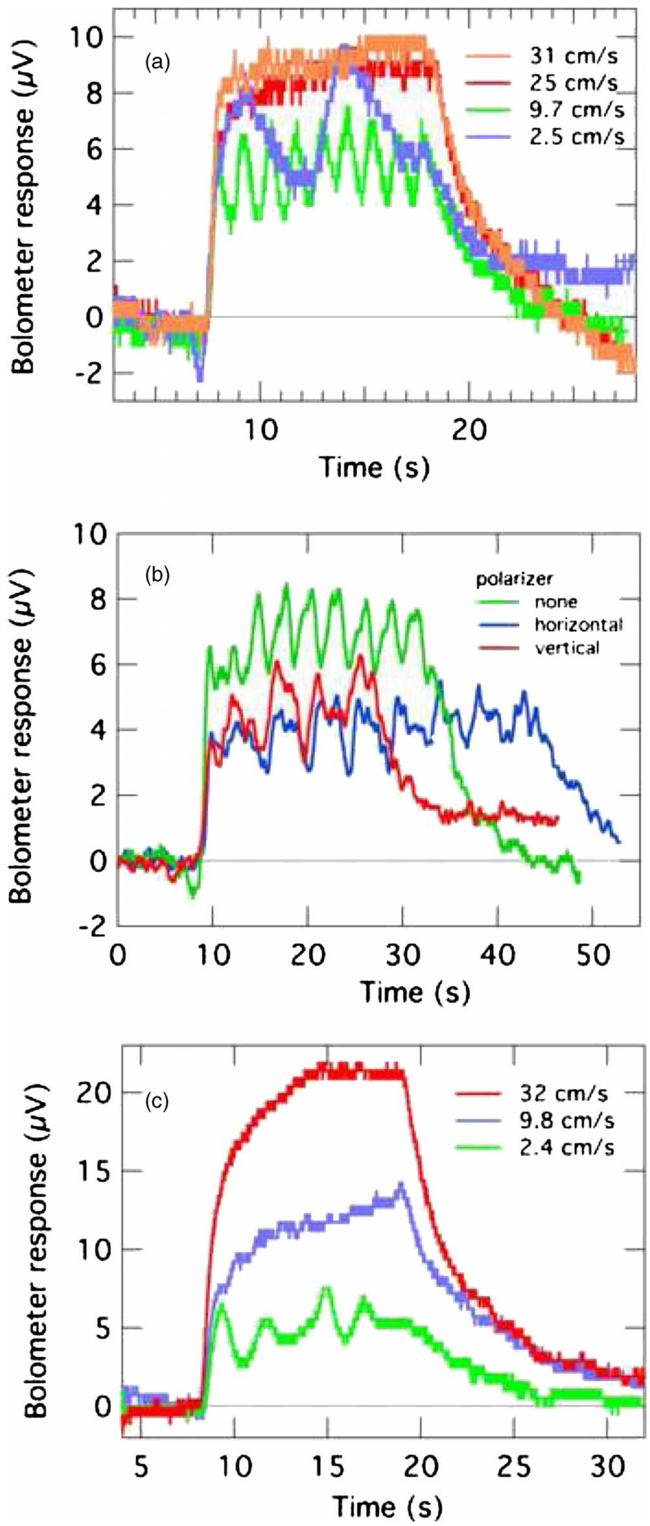

Fig. 2. (Color online) Time evolution of the terahertz signal on unwinding single-sided adhesive tape. (a) Bolometer signal as a function of time for different tape speeds. At ~8 s the adhesive tape begins unwinding. The oscillations from ~8 to ~18 s are in phase with the spool rotation. At ~18 s, unwinding stops. A small drift of the background signal is sometimes evident. (b) Passing the terahertz radiation through a polarizer oriented either horizontally or vertically does not change its amplitude. This amplitude is about half of that without the polarizer. (c) Terahertz radiation from double-sided sticky tape for different tape speeds.

THz emission. While the tape remained adhesive, a THz signal was generated. The time evolution and the dependence on drive speed both become more variable with repeated unwinding. This is related to the uneven distribution of strongly adhering sections on the rewound tape.

We investigated the polarization of the emitted THz radiation [Fig. 2(b)]. We measured the radiation first without a polarizer, then with the wire grids of the polarizer in the same direction as the peeling line on the tape, then with the wire grid perpendicular. The THz signal was of the same magnitude for both directions of the polarizer, and this magnitude was about half the signal level without the polarizer. We conclude that the emitted THz radiation is not linearly polarized.

We ascribe the abrupt increase in the detected THz radiation on unwinding the tape to tribocharging and subsequent discharging. We attribute the much-smaller gradual increase of the detected signal with time on the top of the signal produced by tribocharging to thermal radiation arising from the tape heating upon unwinding. (By thermal radiation we mean radiation at the frequency being detected, in this experiment 0.1–3 THz, originating from a heated body [11].)

There are several reasons to exclude thermal effects as the main source of the abrupt change of bolometer signal. First, the amplitude of the signal did not depend directly on the adhesive strength of different tapes, which would be expected for heating. Rather, the signal seemed to depend on the type of the adhesive and backing material. For example, Scotch Magic 810 tape, with good adhesive strength, and electrical tape, with poor adhesive strength, gave comparable, strong emission. On the other hand, Scotch Everyday 500 tape generated no discernible emission, despite having much stronger adhesion than the electrical tape. These results are consistent with the tribocharging mechanism, where different materials can have surprisingly different charge accumulation [12]. Secondly, a greater driving speed will result in greater heating, but the abrupt increase of the bolometer signal did not change substantially with driving speed [Fig. 2(a)]. Thirdly, there is a glow of bluish light along the line of peeling [Fig. 1(b)], visible to the naked eye in darkness. We observe qualitatively that a stronger glow corresponded to stronger THz emission. Thermal radiation cannot be the origin of the glow. We conclude that the visible and THz radiation have a common origin in tribocharging, not heating. Following tribocharging, different mechanisms are responsible for the optical and terahertz emissions.

These conclusions are supported by measurements using a double-sided adhesive tape, Scotch 665. In contrast to the single-sided tape [Fig. 2(a)], there was a gradual increase in THz signal as unwinding commenced, and the amplitude depended strongly on the unwinding speed [Fig. 2(c)]. Both the increase and the decrease of the signal for the double-sided tape occur exponentially with time. We ascribe the radiation emitted on peeling the double-sided tape to heating. Unwinding double-sided tape will produce much less tribocharging than a single-sided tape, since the two separating surfaces are the same. On the other hand, increased adhesion results in stronger thermal radiation that in turn increases with driving speed.

Finally, we measured the THz spectrum (Fig. 3) directly by placing the tape at the focus of the emission port of a Bomem DA8 Fourier-Transform spectrometer. Three different cold filters, with high-frequency cutoffs of approximately 3, 12, and 24 THz, were used for the three traces in Fig. 3. These were matched with a 23 μm Mylar, 6 μm Mylar, and broadband beam splitter, respectively. The spectral resolution was 0.12 THz, and the signal-to-noise ratio was ~1000:1.

We took a spectrum with the tape stationary then a spectrum with the tape unwinding; the ratio of these is plotted in Fig. 3. Many repeated runs yielded the same result. We make three remarks. First, there is weak but measurable THz emission over each of the three spectral ranges. Second, the radiation is not equally intense at all frequencies, nor does it increase systematically with frequency. Rather, it has a broad peak at about 2 THz, a dip, then a steady rise to 18 THz, where there may be a second peak. Third, the fine structure originates mainly in the incomplete ratioing of the instrument filters and residual water vapor and is not fine structure in the emission spectrum.

In conclusion, the visible glow and THz emission result from tribocharging, which in insulators is associated with the transfer of ions, rather than electrons, between two different materials [12–14]. Static discharge and the deceleration of free ions is the most likely mechanism for the THz radiation, resulting in a broad radiation spectrum (Fig. 3). This is different than the spectrum produced by bremsstrahlung in a nonabsorbing plasma [15], as inferred from x-ray spectra in vacuum [8], which exhibits a continuous decrease of power with frequency. Our THz spectrum resembles the bremsstrahlung in a plasma with absorption [16]. The lack of polarization we observe is consistent with this mechanism. Such processes are of interest in stars and nebulae [15,16]. Understanding the mechanism in detail may lead to increased power below 3 THz, the major challenge in developing THz sources based on tribocharging. Prospects for new THz sources more broadly involve utilizing electric fields [17], temperature change [18], or ultrasound [19]. An immediate task is to investigate the THz emission of tape peeling in a vacuum. While the power observed to date is small (<1 μW), we believe further optimization is possible (by investigating further tape types, rotation speeds, and the angular distribution) and may lead to practical compact, inexpensive sources useful at least from 1 to 20 THz.

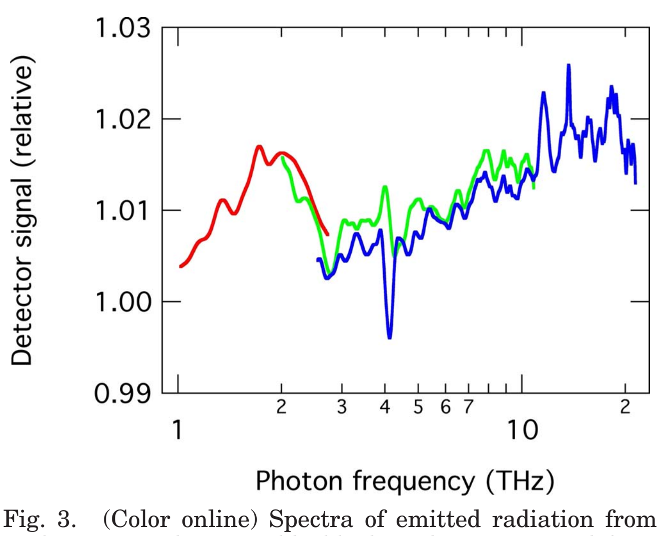

Fig. 3. (Color online) Spectra of emitted radiation from peeling tape relative to blackbody radiation emitted from stationary tape. The three spectra were taken using different combinations of beam splitters and optical filters for the three frequency ranges concerned. The sharp peaks above 10 THz are an experimental artefact.

Evan Constable and Yunfei Hu helped with some measurements. Rodney Vickers assisted with spectrometer alignment. The University of Wollongong supported the work.

[†]The authors contributed equally to this work.

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