A new continuously tunable submillimeter source for spectroscopy and other high-resolution applications has been developed. In this source the optical spectrum of a mode-locked femtosecond laser is downconverted into the submillimeter region by the demodulation process of a photoconductive switch. The power generated is subsequently radiated into free space by an antenna which is integrated along with the switch on low-temperature grown GaAs. The very high resolution is ultimately traceable to the cavity length of the laser and the stable mode-lock frequency which results. Among the most important attributes of the sources are straightforward absolute frequency calibration, very high spectral purity, and the potential for spectral multiplexing. © 1995 American Institute of Physics.

Methods have long been sought for the generation of tunable electromagnetic radiation in the gap between the bounds defined by traditional microwave technology at long wavelength and optical/laser sources at shorter wavelength. Approaches to this problem have included a series of advances in nonlinear frequency multiplication and cooled detector development,1–4 the extension of fundamental electron beam oscillators5–7 and fundamental solid-state oscillators to higher frequency,8–10 and optical heterodyne down conversion.11–17

In this letter we report an alternative, the demodulation of a mode-locked femtosecond laser pulse train by means of a subpicosecond photoconductive switch (PCS) fabricated on low-temperature grown GaAs (LTG-GaAs).19 In these sources submillimeter wave (SMM) radiation is produced by the demodulation of an optical pulse train by photoconductive phenomena and the conduction of the resulting current through a radiating log spiral antenna. The frequency domain spectrum is given by the Fourier transform of the envelope of the time domain optical pulse train, convoluted with the time response of the photoconductive phenomena and the radiative structure. In the absence of signal processing, this results in a comb of frequencies which are exact multiples of the laser mode-lock frequency. These begin at the lowest frequency efficiently radiated by the antenna and extend to higher frequency until limited either by the laser pulse width, the speed of the photoconductive switch, or the radiative properties of the antenna. In these experiments the frequencies that make up the comb are swept by varying the length of the cavity of the mode-locked laser and the elements of the comb selected by a grating. This source has the attractive features of extremely high spectral purity and stability, straightforward absolute frequency calibration, natural multiplex capabilities, and simplicity.

Recently, a new generation of PCS has been developed which offers unprecedented bandwidth and breakdown voltage.17,19 In the PCS-based source described here, the SMM radiation is produced by the generation of electron-hole pairs in LTG-GaAs and the subsequent drift of the carriers to biased electrodes. The drifting photocarriers generate a current in the external circuit, in this case a spiral antenna. The gap between the electrodes is 2.0 μm wide, which is substantially less than the gap size used in typical PCS devices. This dimension was chosen to get high switch responsibility consistent with the LTG-GaAs epitaxial thickness of 1.5 μm and the total active area of 8×8 μm. Experience has shown that when the gap between the electrodes is much less than about 1 μm in a PCS of this small area, the device is too easily shorted by a typical mode-locked laser pulse, leading to saturation of the photocurrent. On the other hand, when the gaps get much wider than the thickness of the LTG-GaAs epitaxial layer, the dc bias voltage is limited by breakdown in the semi-insulating substrate, leading to reduced responsivity.

In principle the bandwidth of the present PCS is determined by the electron-hole recombination time τeh. Separate measurements of τeh by time-resolved photoreflectance yield a value of approximately 250 fs, corresponding to a 3 dB PCS power bandwidth of ~600 GHz. The other possible intrinsic limitation on the bandwidth is the RC time constant associated with the resistance of the antenna (~72 Ω) and the capacitance of the interdigitated electrodes (~1.1 fF), which corresponds to a time constant of ~100 fs. Heterodyne downconversion using this PCS design excited by two cw optical lasers has demonstrated the ability to generate tunable radiation from 100 GHz–1 THz for spectroscopy.20,21 Other PCSs have been used to generate...
short pulses of broadband SMM radiation\textsuperscript{22–25}

The experimental system is shown in Fig. 1. A self-mode-locked Ti:sapphire laser of standard design\textsuperscript{26} was modified so that its length and fundamental mode-lock frequency could be varied, slowly via a translation stage and more rapidly via a piezoelectric transducer (PZT). The mode-lock frequency is measured using a photodetector and frequency counter. This laser produces pulses of \( \sim 100 \) fs width, has an \( \sim 82 \) MHz mode-lock frequency, and average power of 250 mW. About 10\% of this power is used to drive the PCS. The mode-lock frequency of the laser was stable (\( \pm 1 \) count) to 1 Hz over many 1 s counting periods. This stability can be attributed at least in part to the average over the \( 10^8 \) pulses in the counting period.\textsuperscript{27} Although this stability (\( \sim 1/10^9 \)) exceeds that required for Doppler limited spectroscopy, it could be increased either by improved thermal stabilization or active feedback.

The power in a given harmonic may be estimated if one assumes that the optical pulses induce a photocurrent that electrically shorts the biased electrodes for the duration of the carrier lifetime (\( \sim 400 \) fs). For a typical bias voltage \( V_b \sim 10 \) V and a dynamic impedance of \( Z \sim 72 \) \( \Omega \) for the antenna, the average power switched by the PCS for a duty cycle of \( 4 \times 10^{-5} \) is \( (4 \times 10^{-5}) \frac{V_b^2}{Z} \sim 40 \) \( \mu W \). Assuming a uniform distribution of \( \pm 1 \) count) to 1 Hz over many 1 s counting periods. This stability can be attributed at least in part to the average over the \( 10^8 \) pulses in the counting period.\textsuperscript{27} Although this stability (\( \sim 1/10^9 \)) exceeds that required for Doppler limited spectroscopy, it could be increased either by improved thermal stabilization or active feedback.

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The SMM radiation emitted by the antenna passes through the GaAs substrate, is coupled into free space by an abutted hemispherical lens, dispersed by an echelon grating, and passed through a gas absorption cell before detection by a cooled Si bolometer. The grating and detector aperture act as a bandpass filter, rejecting spectral components outside the range of interest. For diagnostics of the source, a Fourier transform interferometer was placed between the grating and the detector. Figure 2 compares the envelope of the spectral output from the grating to the signal emitted by the PCS alone.

Without bandpass filtering, the spectrum generated in the SMM by this source is a comb of lines separated by the optical mode spacing \( f_0 = c/2l \), which can be tuned via adjustment of the cavity length. The envelope of this SMM comb is determined by the convolution of the optical comb and the frequency dependence of the PCS. In the absence of the grating \( \sim 5 \times 10^3 \) individual components exist and the

![FIG. 1. The experimental system.](http://ojps.aip.org/aplo/aplcr.jsp)
indicative of any broadening in the source itself.

Although measurements of spectral purity in the frequency domain at very high frequency (~10^12 Hz) are related to spectral and temporal measurements near the mode-lock frequency (~10^9 Hz), in large part they depend upon different parts of the noise spectrum of the driving source. The relationships among these measurements are complex and worthy of further consideration.

From these measurements we conclude that even without any special efforts to stabilize the laser, the spectral purity of the source exceeds that necessary for high-resolution gas phase spectroscopy. This high spectral purity is a result of the correlations among the changes in the optical frequencies of the different modes due to mirror vibrations, etc. Thus the absolute instability in the difference frequency in the SMM produced by the mixer is smaller than the absolute instability of one of these modes in the optical by the ratio \( v_{\text{optical}}/v_{\text{SMM}} \), a number of the order 10^5. Moreover, because the frequency is an integer multiple of the mode-lock frequency, it is possible to establish the absolute frequency by simple electronic means.

The large number of harmonics simultaneously present in femtosecond demodulation sources presents both a problem and an opportunity. In our demonstration we have adopted the simple expedient of selecting only a portion of the radiated harmonics via a grating. The alternative of replacing a single detector element with an array would provide the opportunity of simultaneously recording, at high resolution, a number of different comb frequencies. Either of these configurations is useful spectroscopically because the sparseness of the high-resolution spectra of many molecules combined with accurate theoretical techniques can be used to identify readily the harmonic in which the absorption occurs. Alternatively, it is possible to increase the effective mode-lock frequency by straightforward multiple reflection schemes or to employ higher mode-lock frequency lasers to reduce the number of harmonics present by one or two orders of magnitude. Such a system would offer an unprecedented combination of cw and pulse multiplex capabilities for the SMM spectral region.

In summary, we have used a LTG-GaAs based PCS to demodulate and down convert an optical femtosecond pulse train into the SMM spectral region. The resulting SMM source is continuously tunable, with absolute frequency calibration, and has very high spectral purity. Additionally, multiplex signal processing options exist which make possible the development of SMM radiation sources which range from the spectrally pure cw to those with picosecond time resolution.

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