Log-periodic antennas for pulsed terahertz radiation

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A new type of log-periodic antenna, the wire log-spiral, has been designed and implemented on GaAs substrates with low-temperature grown GaAs photoconductors. The new antenna is compared to two traditional antenna designs (log-periodic and dipole) used for the detection of pulsed THz radiation.

Microwave pulses, with terahertz bandwidth and picosecond duration, can be generated using standard femtosecond laser techniques, and detected using a 1/2 wave dipole antenna[1,2] or dipole-like horn.[3] This antenna is typically 100 μm long and fabricated on a short carrier lifetime substrate, such as ion-implanted silicon on sapphire. The received signal is then electrically gated with the same femtosecond laser that is used to generate the rf. Gates are photolithographically defined at the center or feed point of the dipole.

This letter reports on the design, fabrication, and initial performance demonstration of two types of antennas for the detection of broadband pulsed THz radiation. One is a standard log-periodic antenna;[4,5] the other is a new design, the wire log-spiral (WLS) antenna. The new antenna is compared experimentally with a dipole and a standard log-periodic design.

Log-periodic (LP) antennas are a family of *frequency-independent* antennas. Their large bandwidth is due to the repetition of a pattern or cell. One advantage of these designs is that it is resonant at $\sim$4 times the free-space wavelength for *both* the largest *and* smallest cell.[5] The inset in Fig. 2(b) shows an outline of the LP antenna used in this work.[3,4] The shaded area represents a single cell or tooth and can be seen to be a resonant monopole by allowing the horizontal dimension to go to zero.[6] Nonplanar implementations can narrow the beam pattern of a given antenna, but are not considered here for practical reasons. For a given design the number of elements in an antenna can be increased. This reduces the impedance for symmetrically connected arms, as long as the electrodes do not overlap. The requirements for good antenna performance are the avoidance of edge effects and near constant impedance (at the feed point) over the entire frequency band.

Edge effects can be avoided by making the antenna large relative to the lowest frequency, or about 1/2 of the longest wavelength.[7] Both periodic designs considered here are $\approx$1 mm across the longest dimension. The increasing impedance of the antenna with radius causes any resonant section to propagate received energy toward the feed point in a backward wave configuration. This also tends to eliminate edge effects.

A recently introduced variation of a LP antenna is the LP-sinuous spiral.[8] This design is expected to offer better frequency coverage since the circular nature of the antenna produces a continuous range of resonances. By reducing this design to a series of *non*concentric half circles, the WLS structure results and is shown in the inset of Fig. 1(b).

A THz rf pulse was obtained by illuminating an InP wafer with $\sim$50 μJ, $\sim$100 fs full width at half maximum (FWHM) visible optical pulses derived from a 10 Hz amplified colliding pulse mode dye laser system.[1,9] All antennas were fabricated by deposition of 1-μm-thick by 5-μm-wide gold electrodes on low-temperature grown (LT) GaAs photoconductors.[10]

The requirement of constant impedance is critical for antennas which are fed by 50 Ω feed lines. In the original implementations operating at <1 GHz great care was taken to integrate the coaxial feed cable into the structure (structures ranged from a few centimeters to meters in size).[4–7] In the structures considered here, the feed point at the center of the antenna is a photoconductive switch, which samples or gates the incoming rf signal.

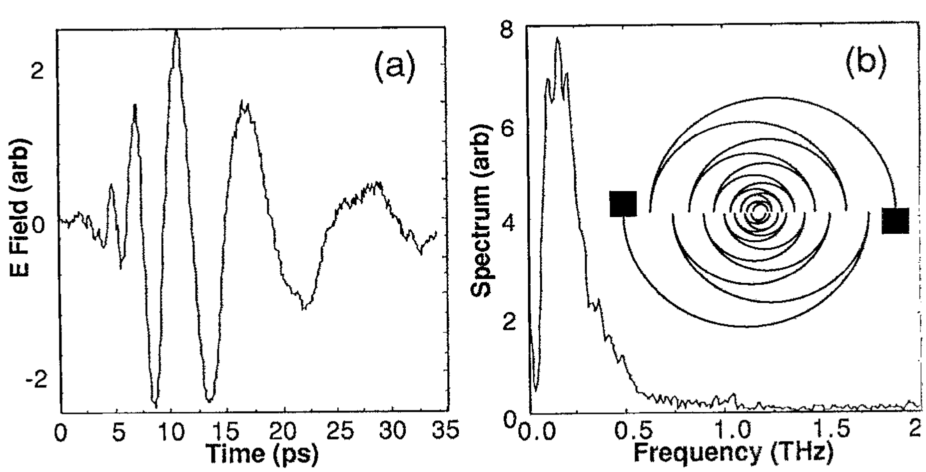

FIG. 1. Wire log-spiral antenna. (a) Measured time waveform, $E(t)$. (b) Fourier transform of $E(t)$. Inset shows electrode pattern. Line width is 5 μm and contact pads are 100×100 μm.

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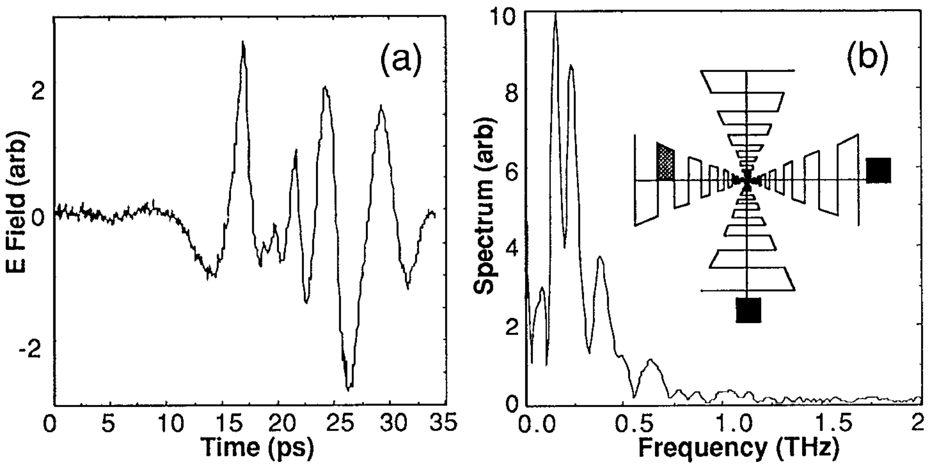

FIG. 2. Log-periodic antenna. (a) Measured time waveform, $E(t)$. (b) Fourier transform of $E(t)$. Inset shows electrode pattern. Bottom and left elements and top and right elements are connected. Shaded portion of pattern represents a resonant element or tooth. Line width is 5 μm and contact pads are 100×100 μm.

A sapphire hyper-hemispherical lens was placed directly on top of the antennas to focus the received rf pulse and minimize the dielectric discontinuity. The gated, low-frequency signals are then read from the antenna contact pads, using the antenna simply as a wire connecting the pad and feed point. For antennas which are gated in this way, the constant impedance requirement does not appear to be important (the switch effectively mixes the rf down to the laser repetition rate *at the feed point*). Although an impedance mismatch between the antennas and the photoconductive gate is likely, detected reflections were found to come from the backside of the wafer on which the antenna was fabricated. These reflections were delayed by backing the antenna substrate with several blank wafers of GaAs. Peak detected signals were several hundred millivolts at a current gain of 10^8 A/V. Signals were acquired using a current preamp and boxcar averager because of the low (10 Hz) repetition rate. The rf pulse was strongly polarized due to the orientation of the InP wafer, requiring correct antenna orientation. This was confirmed using a wire grid polarizer. A single experimental scan (acquisition time of ~ 1 min) of the electric field, $E(t)$, incident on the WLS antenna as a function of gate delay time is shown in Fig. 1(a). Figure 1(b) shows the Fourier transform of $E(t)$.

Analogous $E(t)$ data for the LP antenna is shown in Figs. 2(a) and 2(b). Unlike the WLS antenna, peaks appear in the frequency spectrum. We note that the LP design presented here is polarization independent, since it contains four arms (this can be thought of as two two-element antennas superimposed, with a concurrent reduction in impedance[11]). The WLS design has two arms, and manifests a polarization-dependent response. Both designs produce peak amplitudes similar to a dipole antenna, but an order of magnitude larger total energies are detected due to the broader spectral coverage.

The frequency dispersion (chirp) observed for both periodic antennas is a consequence of the propagation time required for longer wavelength signals to reach the feed point of the antenna, and has been previously observed in another antenna type.[12] This dispersion can be advantageous (if linear) when analyzing spectral response, as the time axis of Figs. 1(a) and 2(a) can also be viewed as the frequency axis. The phase of the Fourier transform was observed to be nearly linear. In addition, by arbitrarily setting the phase of the transform to zero and performing an inverse Fourier transform (zero phase transform), the chirp can be removed. This is shown in Fig. 3 for a dipole antenna before (heavy line) and after the zero phase transform. Since the dipole is a resonant structure, not much residual energy is seen in the wings outside the main pulse. The zero phase transform of the WLS antenna is shown in Fig. 4(a) and the overall response is very similar to the dipole, with very little energy outside the main pulse. In Fig. 4(b) the LP antenna is seen to have a very different zero phase transformation, with significant energy outside the main pulse. With both periodic antennas producing nearly linear phase responses, the difference in the zero

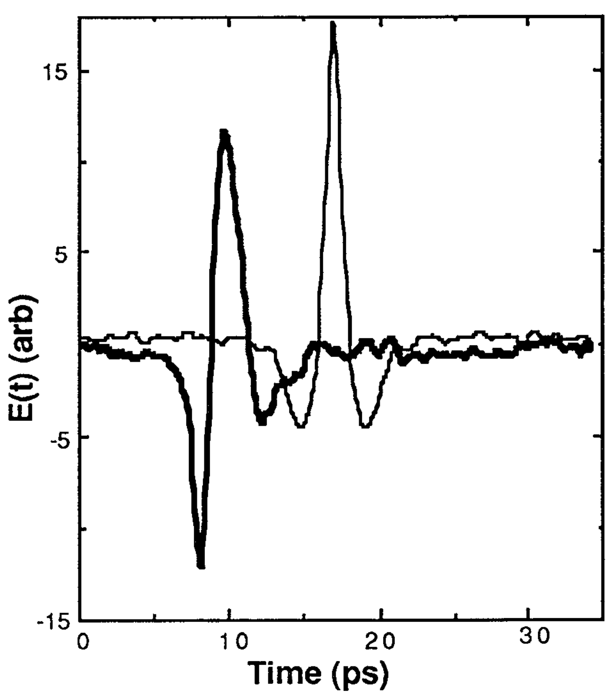

FIG. 3. Dipole antenna response (heavy line) and response after the phase of the Fourier transform is set to zero and the inverse transform taken (zero phase transformation). Time shift is an artifact of the process.

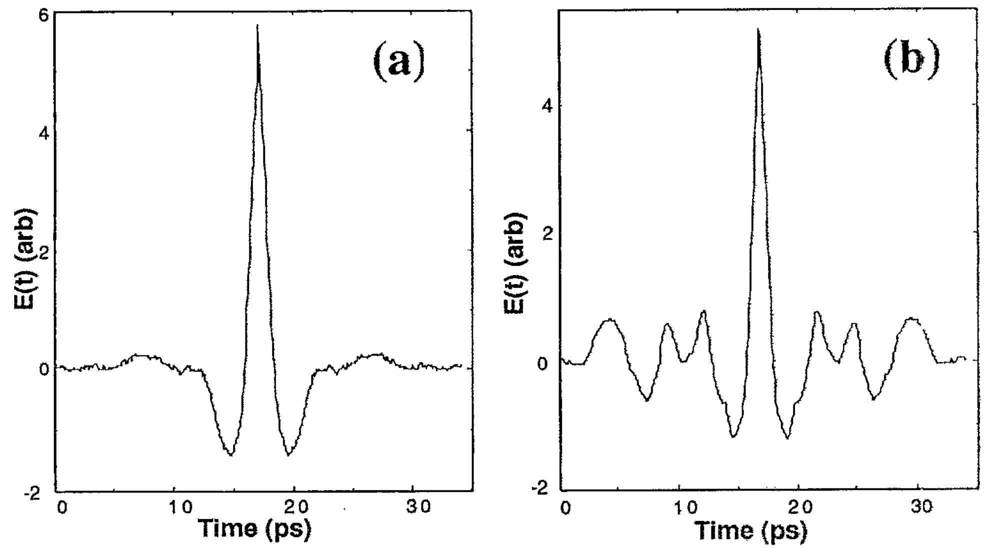

FIG. 4. (a) Spiral antenna response after zero phase transformation. (b) Log-periodic response after zero phase transformation showing poor frequency uniformity.

phase transformations must be due the nonuniform spectrum of the LP antenna.

As these preliminary results were obtained using a photoconductor with a carrier recombination time of ~ 1 ps, the upper frequency detectable by these antennas was limited to ~ 1 THz. As our understanding of LT GaAs improves[13] these broadband, periodic structures will provide improved sensitivity and greater bandwidth. The smallest feature size is 10–20 μm, so the highest *received* (as distinguished from detected) frequencies could be > 10 THz.

In conclusion, we have demonstrated two log-periodic antenna designs for use with pulsed terahertz light sources. The wire log spiral, a new design, is a simplification of a sinuous log spiral which produces a smooth spectral response. Both periodic types have an order of magnitude better overall response than dipole antennas presently in use.

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