Propagation of half-cycle far infrared pulses

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We have studied the propagation of half-cycle (i.e., unipolar) electromagnetic pulses centered at terahertz frequencies, in free space, through apertures, and through focusing optics. The temporal pulse shape of an apertured half-cycle pulse is significantly altered during propagation, but retains much of its unipolar character after traveling more than 20 times the aperture dimension. When focused by an achromatic lens, a half-cycle pulse evolves into a single-cycle pulse at the focal waist and an inverted half-cycle pulse in the far field.

1. INTRODUCTION

Subpicosecond far infrared (FIR) pulses in the 0.5–5 THz range have been made by use of biased transmission lines coupled to dipole antennas,\(^1\) Cherenkov radiation in polarizable media,\(^2\) and in large-aperture photoconductors.\(^3,4\) These pulses can have temporal shapes from less than one cycle\(^5\) to many cycles.\(^5\) Pulses lasting less than a single cycle have coherent bandwidths greater than their peak or central frequency. Such pulses are nearly unipolar: the electric-field strength is much greater along one sense of the polarization direction than the other, hence the term half-cycle pulse. This property has led to their use as fast electric-field pulses in nonlinear optics\(^7\) and as tools for sculpting and analyzing Rydberg states in atoms.\(^8–11\) There are additional applications for this novel radiation in linear absorption spectroscopy.\(^12\)

These new applications require detailed knowledge of the FIR temporal pulse shape and spectrum. Two different techniques, gated sampling and interferometry, have been developed to obtain this information. In photoconductive\(^13\) and electro-optic sampling,\(^14\) the amplitude and phase of a repetitive time-varying electric waveform can be measured directly. Electric-field interferometry measures the field autocorrelation, from which the spectrum may be obtained with a Fourier transform.\(^15\)

Both sampling and interferometry require propagating the beam through optical paths that are large compared with the antenna size. In this case differential diffraction loss of wide-ranging frequency components can be a major source of temporal distortion. Loss of intensity on-axis due to diffraction varies inversely with the square of the frequency; consequently, after the pulse propagates some distance, the power spectrum of the FIR pulse on-axis will lose low-frequency components that may have been present at the transmitter. In addition, different frequencies are subject to different phase shifts, so the FIR pulse will generally have different shapes depending on the experimental configuration and the propagation distance. If the pulse is focused by lenses or mirrors, the pulse shape can be more severely altered, since the differential loss from diffraction for the high- and low-frequency components are magnified owing to focusing. These effects can be minimized by limiting the propagation distance and avoiding focusing optics, but generally this is not practical.

Little has been published on the theory of mode propagation of such short pulses. In this report we analyze the change of an FIR half-cycle pulse as it propagates in free space as well as through focusing optics and apertures. We present a detailed analysis based on Gaussian solutions to the wave equation and demonstrate the distortions for model examples.

The FIR pulse shape at the transmitter is determined by the exciting laser pulse and the physical characteristics of the antenna. This is not our main subject here, but it has been studied extensively.\(^7,16–18\) We are primarily interested in propagation of broadband coherent FIR produced in large-aperture structures, by which we mean that the generating structure is much larger than the central wavelength of the radiation. Large-aperture antennas have radiation patterns that are determined by the relative phase of the radiation produced at different parts of the structure. Simply put, the radiation peaks in the direction for which the phases are matched; i.e., where they add constructively. One very simple approach to FIR large arrays is to drive the current in the antenna directly by optical excitation of a single, large-area, nonlinear dielectric or photoconducting switch. Then the radiation maximum is in the direction of transmission or specular reflection of the exciting light pulse. This method has been used to generate FIR by transient current surge in semiconductors;\(^16\) from optical rectification, a \(\chi^{(2)}\) process;\(^17\) in noncentrosymmetric materials; from field-induced optical rectification, a \(\chi^{(3)}\) process;\(^18\) or from \(\chi^{(4)}\) nonlinear frequency mixing.\(^7\)

In the current surge mechanism, photocarriers are created by optical excitation and subsequently accelerated by an external bias field or internal depletion field. The transient current following photoexcitation increases from near zero to a finite value, and the time-varying transverse field that propagates away from the surface is proportional to the current derivative \(dI/dt\); therefore this transient pulse is unipolar. The temporal envelope of the FIR pulse at the source depends on the laser pulse shape and other factors. The current is proportional to
the product of the local electric field and the carrier density, which both change with time and laser fluence. In our own studies we have found that the carrier density is proportional to the fluence of the initiating laser pulse within some range: in GaAs illuminated by subpicosecond pulses at 780 nm and a repetition rate of 10 Hz, fluences below 40 μJ/cm² are in this linear regime. The mechanism responsible for saturation at higher fluences is not yet fully understood.

FIR radiation produced by the parametric methods of optical rectification or field-induced optical rectification is likewise linear with laser intensity. In addition, these parametric generation mechanisms produce a pulse that follows the temporal envelope of the laser excitation. In the case of the fourth-order nonlinear frequency mixing, the FIR field is proportional to the square of the laser intensity.

To illustrate propagation effects, we choose a model laser pulse with a Gaussian temporal and spatial profile, exciting a semiconductor antenna. Propagation of the optical pulse is accurately described by the Gaussian solutions of the standard wave equations. If the amplitude of the laser pulse is given by

$$F(r, z = 0, \phi, \omega) = \sqrt{\pi} \tau F_0 \exp \left[ -\frac{\omega^2 \tau^2}{4} - \frac{r^2}{R^2} \right].$$

Equation (1) can be used to describe each frequency mode. Obviously, every frequency component is a Gaussian mode and has the same initial phase and waist, equal to the beam width of the exciting laser. The phase and amplitude of every frequency component may be calculated at any propagation distance away from the source. An inverse Fourier transform then gives the FIR pulse shape.

At the position of the antenna, the FIR spectrum has nonvanishing components at zero and near-zero frequencies. This violates the validity of the Gaussian solutions. The problem is easily solved, however, because the antenna has a finite aperture size, so we may terminate the integral at some finite wavelength. In our calculation the antenna dimension determines this cut-off wavelength and cut-off frequency. The physical meaning of the cutoff is that low-frequency components, including zero frequency, diffract away into a 4π solid angle as soon as they leave the FIR emitter, so they do not contribute to the field traveling in the specular direction. They will not be included in our calculation.

Scalar diffraction theory may also be used to calculate the FIR pulse shape, in which case the low frequencies may be included in the calculation as well. However, this approach is much more involved and does not offer an intuitive insight into the propagation process.

2. PROPAGATION OF FAR-INFRARED PULSES IN FREE SPACE

The simplest configuration is one in which the FIR pulse is emitted from the semiconductor wafer and propagates to the detector without going through any optics. The propagation mode for every frequency is completely determined by Eq. (1) for given waist size $w_0$ and confocal parameter $z_0$. For the FIR pulse under consideration, all the frequency components have the same waist, which is located on the surface of the emitter. They stay in the original mode regardless of the propagation distance. So Eq. (1) directly gives the amplitude for frequency $\omega$ at the detector located at $z$, except that $F_0$ in Eq. (1) should be replaced by the initial amplitude for frequency $\omega$ given by Eq. (5). The pulse shape is simply calculated from the inverse Fourier transform.

Numerical techniques are used to perform the inverse Fourier transform. The cut-off frequency determines the lower limit for the integral. For a 2-cm aperture, it has a value of 15 GHz. In Fig. 1 we show results for the field shape on-axis at different propagation distances $z$ for a 2-cm waist size. An original half-cycle pulse of 500 fs duration is assumed.

Clearly the temporal shape of the FIR pulse is changed, and a negative tail appears in the pulse. The electromagnetic field appears to oscillate faster.
spectra at different distances \( z \) are plotted in Fig. 2. At large \( z \), the peak of the spectrum is shifted to a higher frequency. This is due to greater diffraction loss for lower frequency components. Nonetheless, the pulse retains its general shape, even after propagation over many times the source dimension.\(^4\)

The off-axis FIR pulse is not shown here. It has a similar frequency spectrum, but it peaks at a slightly lower frequency than on-axis. The high-frequency components are more concentrated around the axis, whereas low-frequency components are distributed more uniformly in the cross section, and a significant part of their energy is off-axis. The FIR pulse is also expected to be slightly broader off-axis, owing to the loss of the highest frequencies.

3. PROPAGATION OF FAR-INFRARED PULSES THROUGH FOCUSING OPTICS

If lenses or mirrors are placed between the transmitter and the detector, the radiation mode is altered in a way that can be described by an \( ABCD \) transformation matrix.\(^20\) Every frequency has a different waist size and location after transformation. The phase is also different from the original mode.

Chromatic aberration is a major concern in designing lenses for broadband coherent radiation. In practice,
pulse. As the pulse propagates towards the focal waist, the trailing edge of the pulse steepens, the period of the first half-cycle becomes shorter, and a temporal node moves toward the center of the pulse. At the focus the pulse becomes a full cycle. As the pulse propagates past the focus, the node moves toward the leading part of the pulse. The pulse gradually becomes nearly half-cycle again but is inverted.

Some insight about the evolution of the FIR pulse comes from an examination of its on-axis spectrum at different distances from the FIR transmitter. Results are plotted in Fig. 5. Clearly, the spectrum at the focal point \(z = 25\, \text{cm}\) is significantly different from the spectrum at the lens \(z = 10\, \text{cm}\). Low-frequency components are severely attenuated compared with the high-frequency components owing to different waist size and location. Most of the high-frequency components are tightly focused at the focal point, where the pulse appears as a full cycle and the spectral bandwidth is approximately equal to the central frequency. As the FIR pulse moves beyond the focus, the high-frequency components begin to diverge, while the low-frequency components are still converging. This reduces the differential diffraction loss on-axis. Therefore the frequency composition starts to become closer to the original pulse. At \(z = 40\, \text{cm}\) the spectrum becomes similar to the original pulse. In addition to the change in spectrum, every frequency component goes through an extra phase shift of \(\pi\) [calculated from \(\eta(z)\)] as the pulse travels through the focus. Therefore the FIR pulse becomes half-cycle at large \(z\), but has an opposite phase and is inverted with respect to the original pulse.

For the same focal length and cut-off frequency, the spectral width dictates how tightly the single-cycle pulse can be focused. Because higher frequency components can be focused more tightly, the larger the spectral width, the smaller the spot size at the focus, since a large fraction of the spectrum is in the high-frequency region.

4. CONCLUSIONS

In conclusion, we have calculated the variation of an FIR half-cycle pulse shape when it propagates in free space and through a focusing lens. The differential diffraction loss is found to change the frequency composition of the pulse depending on the propagation distance. As a result the pulse shape is altered. When focusing optics are present, this effect is magnified and we obtain a full-cycle pulse at the beam focus and an inverted half-cycle pulse at far field. These results have important implications for any applications that use the unipolar character or the broad spectral bandwidth of half-cycle pulses.

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