1 April 2000

Optics Communications 176 (2000) 429–435

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Tunneling of single-cycle terahertz pulses through waveguides

Klaas Wynne *, John J. Carey, Justyna Zawadzka, Dino A. Jaroszynski

Femtosecond Research Centre, University of Strathclyde, Dept. of Physics and Applied Physics, Glasgow, G4 0NG, UK

Received 13 December 1999; accepted 25 January 2000

Abstract

Propagation of single-cycle terahertz pulses through and past wavelength-sized metal structures has been studied experimentally. In waveguides close to cutoff, it is found that the phase velocity can become superluminal and even negative. Multiple reflections of evanescent waves inside the waveguide are found to be the cause of a negative phase velocity below the cutoff frequency. The centroid delay of terahertz pulses propagating past a thin metal wire is found to be advanced or delayed depending on the polarization with respect to the wire. In all cases of superluminal propagation described here, the principle of causality is preserved. In a restricted sense, exchange of information faster than the speed of light is found possible, however, the principle of causality ensures that information cannot advance by more than the inverse bandwidth of the signal. This eliminates causal-loop paradoxes and ensures that faster-than-light communication is not practical. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 42.25.Bs; 73.40.Gk; 42.65.Re; 03.65.Bz

1. Introduction

It has been known for a long time [1] that electromagnetic waves can travel with superluminal velocity in regions of anomalous dispersion or evanescent propagation. Experimental studies have confirmed that the phase and even group velocity can exceed the speed of light in vacuum. This has naturally brought up the question whether superluminal exchange of information is possible or not. Past microwave experiments [2,3] have used either CW radiation or very long pulses and could not directly observe the propagation velocity of energy packets. Optical experiments [4–6] do not have access to phase information as they only measure intensities rather than fields. Here we report on novel studies using free-space-propagating nearly single-cycle THz pulses [7,8]. The THz pulses are generated by optical rectification in a small spot, resulting in a beam that, in the near field, has a diameter of 200 μm. As the detection is coherent, the THz-pulse setup gives access to all the pertinent phase and amplitude information of a pulse traveling through a tunnel region while having good time-resolution. Therefore, the propagation characteristics of evanescent waves could be analyzed entirely in the time domain for the first time. In waveguides, it is found that the phase velocity can be superluminal or negative. This may result in the peak of a pulse emerging from a sample before entering it, in apparent but superficial contradiction with causality. Theoretically, the group ve-

* Corresponding author. Tel.: +44-141-548-3381; fax: +44-141-552-2891; e-mail: klaas.wynne@phys.strath.ac.uk

0030-4018/00/$ - see front matter
PII: S0030-4018(00)00542-3

locity in a waveguide below cutoff is superluminal as well but a limited signal-to-noise ratio has prevented us from establishing that. However, in experiments on propagation past metal wires, the unique properties of single-cycle THz pulses could be used to prove that the group velocity is superluminal.

Some of the superluminal propagation effects may be the result of absorptive pulse shaping in which, for example, the system preferentially transmits the front of the pulse. However, pure phase effects contribute to the temporal advance too and may in fact dominate. This can be expressed using the group and loss delays. If the complex field transmission is $\tilde{T}(\omega)$, these delays are given by [9]:

$$\tau_g + i\tau_L = -i\partial \ln \tilde{T}/\partial\omega. \quad (1)$$

The loss delay, τ_L, is related to the delay induced by absorption or reflection that affects the front of the pulse more than the back or vice versa. Many authors have concluded [10] that the loss time (which is often a delay rather than an advance) is most relevant to describe the physics of tunneling but there is no physical or experimental reason for this assertion. It has been argued [1,6,11] that superluminal communication can be ruled out using the principle of causality. A counter argument [12] is that practical signals are bandwidth limited, which makes the principle of causality inapplicable. In fact, practical signals have a power spectrum extending to infinite frequency but with vanishing power. Therefore, we find that non-evanescent waves will always end up dominating the signal at tunnel distances where superluminal communication would otherwise become useful. This rules out the possibility of practical faster-than-light communication.

2. Experimental

Nearly single-cycle THz pulses are generated through optical rectification of femtosecond pulses in ZnTe (see Fig. 1) [8]. The laser source produces ~ 150-fs pulses at 800 nm with a 250-kHz repetition rate. About 280 mW is focused onto a 0.5-mm thickness ⟨110⟩ ZnTe crystal mounted on a translation stage that allows translation perpendicular to the beam. The THz pulses emitted by the crystal are collimated and focused with off-axis parabolic mirrors. The second parabolic mirror has a hole to allow an 800-nm gating beam to be overlapped with the THz beam in an identical ZnTe crystal. The gating beam has 8-mW average power. It is temporally delayed by a fast-scanning (6 Hz) optical delay line, and is focused into the detection crystal. The Pockels effect in the detection crystal causes the ellipticity of the gate beam to change in proportion to the instantaneous electric-field strength of the THz pulse. This time-delay dependent change in ellipticity is measured by sending the gate beam through a quarter-wave plate, a Glan-Thompson polarizer, and balanced detection by a pair of photodiodes. The THz pulses have about one 0.4-ps long cycle and a spectrum that extends from 5 to 100 cm^{-1} (0.15 to 3 THz) [7]. Samples are mounted directly onto the ZnTe generation crystal. In the near field, the THz beam has a diameter of 200 μm [8], which allows very efficient launching of energy into sub-wavelength waveguides.

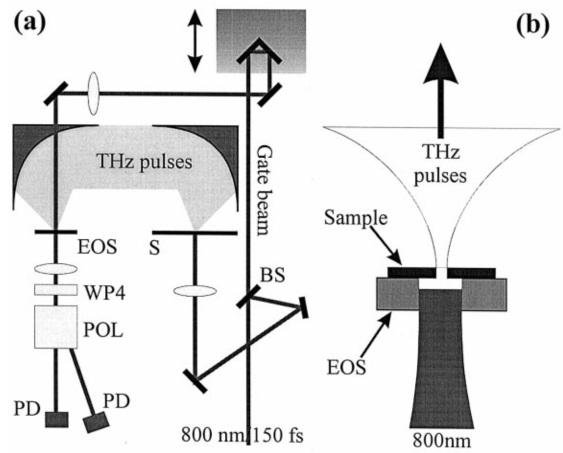

Fig. 1. (a) Schematic diagram of the near-field THz-imaging setup. The THz pulses are generated by optical rectification of 120 fs pulses at 800 nm in ⟨110⟩ ZnTe. BS: Beam splitter, S: sample and generation crystal on $x-y$ translation stage, WP4: $\lambda/4$ plate, EOS: electrooptic detection crystal, POL: polarizer, PD: photodiode. (b) The sample is positioned on the back of the generation crystal, in the near field of the THz beam.

Transmission, refractive-index, and phase spectra are derived from the time-domain data by fast Fourier transformation. If $\tilde{E}(\omega)$ is the FFT of the time-domain data and $\tilde{E}_0(\omega)$ a reference spectrum, the field transmission is given by the absolute value of $\tilde{T}(\omega)$

$= \tilde{E}(\omega)/\tilde{E}_0(\omega)$. Calculation of the accumulated phase (or the refractive index) is slightly problematic as it involves a logarithm of a complex quantity. The method used here is that an overall refractive index is guessed at. The accumulated phase difference with respect to free space, is then calculated from

$$\Delta\varphi(\omega) = \varphi_{\text{guess}} - i\ln\left(\frac{\tilde{T}(\omega)}{|\tilde{T}(\omega)|}\exp\left[-i\left\{\varphi_{\text{guess}} - \frac{\omega L}{c}\right\}\right]\right), \tag{2}$$

where L is the sample length and $\varphi_{\text{guess}} = \omega L n_{\text{guess}}/c$ is the guess for the phase. In the data discussed here, it is a reasonable assumption that the refractive index tends to $n=1$ at high frequencies and using $n_{\text{guess}} = 1$ is consistent with all the data. The phase extracted from the data is used to calculate the effective refractive index from $n = 1 + c\Delta\varphi/(\omega L)$, and the group-delay difference from

$$\Delta\tau_{\text{group}} = \partial(\Delta\varphi)/\partial\omega. \tag{3}$$

To investigate evanescent-wave propagation inside waveguides, several metal cylindrical pinholes have been used such as commercial nickel pinholes with a 40-μm thickness and diameters of 50, 100, 200, and 400 μm. To obtain longer waveguides, holes were drilled though sheet metal mechanically. A 1-mm thickness aluminum plate was used to make 200 and 400-μm wide waveguides. 80 and 250-μm thickness brass plates were used to drill 150 and 200-μm diameter waveguides. As some of these waveguides are shorter than their diameter, it may be expected that end effects will play an important role.

In a perfectly conducting cylindrical waveguide, the electromagnetic waves accumulate phase, which for TE-modes is given by [13]

$$\varphi(\omega) = \frac{\omega_c L}{c}\sqrt{(\omega/\omega_c)^2 - 1}\,,\ \omega_c = \frac{2xc}{d}, \tag{4}$$

where ω_c is the cutoff frequency, d is the waveguide diameter and L its length. For the lowest order TE_{11} mode, the parameter x has the value 1.841 [13]. Above the cutoff frequency, the transmission is unity and the waveguide is dispersive. Below cutoff, transmission is less than unity and the accumulated (real) phase is zero. As the phase delay is φ/c, the phase velocity tends to infinity as cutoff is approached. The group delay derived from Eq. (4) is

$$\tau_{\text{group}} = \frac{\partial\varphi}{\partial\omega} = \frac{\omega L}{c}\frac{1}{\sqrt{\omega^2 - \omega_c^2}}. \tag{5}$$

As cutoff is approached, the group velocity tends to zero. Below cutoff, however, the group delay and group-velocity dispersion are imaginary, which implies an infinite (real) group velocity and minimal pulse broadening. Taken at face value, this may appear to imply that it is possible to transmit information superluminally.

In the initial experiments, relatively large diameter (150 to 400 μm) waveguides were studied, in order to have the cutoff frequency in the middle of the accessible frequency range. Fig. 2 shows a typical case of 200-μm-diameter waveguides of various lengths (TE_{11} cutoff frequency at 29.3 cm^{-1}). The 1-mm length waveguide shows a sharp transmission cutoff as expected. As a 12-ps window had to be applied to the time-domain data, the cutoff is slightly smoother than predicted by theory. The phase properties in the 1-mm case are also as expected: the effective refractive index varies from 1 at high frequencies to 0 at the cutoff frequency and the group delay diverges at the cutoff. However, for the shorter waveguides (40 and 80 μm), the transmission cutoff

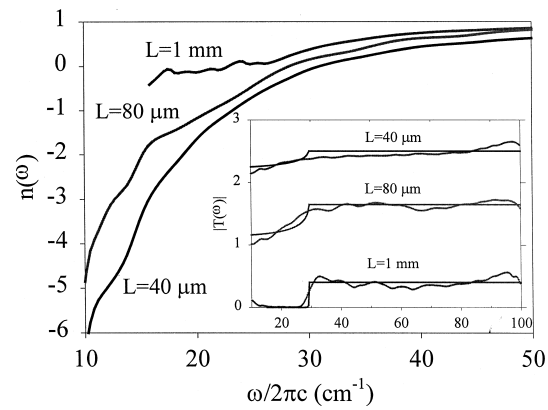

Fig. 2. Experimentally observed evanescent-wave propagation in 200-μm diameter pinholes. (Main) The effective refractive index calculated from the accumulated phase. (Inset) Experimental field transmission $|\tilde{E}(\omega)/\tilde{E}_0(\omega)|$ and comparison with transmission calculated from simple waveguide theory, Eq. (4). The curves have been offset vertically for clarity.

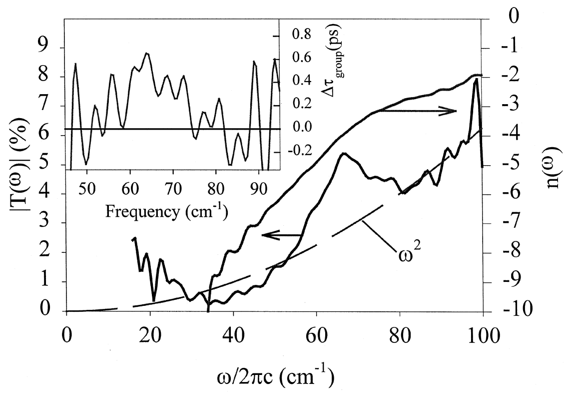

Fig. 3. Propagation through a 50-μm diameter 40-μm length nickel waveguide. Shown are the electric-field transmission and the effective refractive index. The dashed line is a fit to an ω^2 dependence and the inset shows the group delay relative to free-space derived from the experimentally determined phase.

all but disappears and the refractive index is negative below the cutoff frequency. In most of the waveguides, it is found that the peak of the THz pulse is advanced corresponding to a superluminal phase velocity. For example, in a 150-μm diameter, 80-μm-length waveguide, the peak advances by 0.1 ps. However, the center of gravity of the pulse is delayed, consistent with a subluminal group velocity.

In experiments in $d = 50$ μm and 100 μm waveguides, (nearly) all the transmitted light is in evanescent modes as the cutoff frequencies are at 117 and 59 cm^{-1}. In these cases, simple waveguide theory fails to describe the data. It has been predicted [14] that the field transmission through sub-wavelength holes should follow an ω^2 dependence. Approximate fits to such a dependence are shown in Fig. 3 but do not fit the data very well. In these data, it appears that there is a reproducible resonance. This is unexpected as the exponentially decaying evanescent waves cannot interfere and therefore should not give rise to any resonances. In the analysis of the data, surface-plasmon resonances [15] or Ohmic damping [16] of the field has not been included, which may account for the discrepancy. Because the waveguides studied are relatively short, the effects of coupling the radiation in and out dominates. Therefore, superluminal group velocities have not been observed in these waveguides.

Temporal advances have also been observed with THz pulses propagating past metal wires with a diameter of about one wavelength (see Fig. 4). In the case of perpendicular polarization, the transmission minimizes when the beam is centered on the wire and at the same time, the peak of the THz pulse is delayed. In the case of parallel polarization, the field-transmission minimum is twice as low and the pulse-peak delay is negative exhibiting a minimum on either side of the wire. From spectra obtained at the delay maximum/minimum in a 100-μm diameter wire, it is found that the phase velocity varies between c and 0.87 c (perpendicular polarization), and between 1.05 c and 1.43 c (parallel polarization, assuming the effect is constant over a 100-μm path).

To investigate whether there are any superluminal group velocities involved, use was made of one of the unique properties of the single-cycle pulses. As the pulses have a length of about one wavelength, it is straightforward to determine whether the average energy-arrival time is delayed or advanced. To this end the centroid delay was used, defined by:

$$\tau_c = \int_{-\infty}^{\infty} dt\, t I(t) \Big/ \int_{-\infty}^{\infty} dt I(t), \tag{6}$$

where $I(t) \propto E(t)^2$ is the instantaneous intensity, which is proportional to energy. Thus, $I(t)$ is **not** a pulse envelope as the slowly-varying envelope approximation breaks down for single-cycle pulses and an envelope is ill defined. If this approximation can

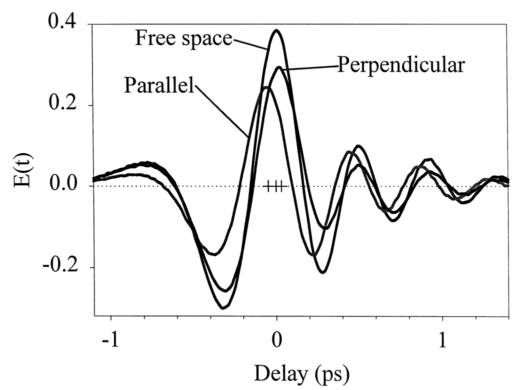

Fig. 4. Sub/superluminal propagation of THz pulses past a 100-μm diameter metal wire. The crosses at 0 fs (free space), +32 fs (parallel) and −47 fs (perpendicular) are the centroid delays calculated over a ±10 ps interval.

be made, it can be shown that the centroid delay is identical to the group delay.

When the centroid delay is calculated from the data in Fig. 4 (propagation past wires), it is found that in the case of parallel polarization, the centroid is advanced ($\tau_c = +32$ fs) and in the case of perpendicular polarization, it is delayed ($\tau_c = -47$ fs). Thus, the centroid delay has the opposite sign to the phase delay. It follows that the average arrival time of the energy can be advanced with respect to propagation through vacuum.

From the expression for the accumulated phase in a waveguide Eq. (4), one can derive the effective index as $n(\omega) = c\varphi/\omega L$. As the waveguide is embedded in air, the interfaces at the waveguide entrance and exit will act as mirrors. Evanescent waves cannot interfere but each reflection off an interface results in a phase shift and a corresponding time shift. As these shifts accumulate on multiple reflections inside the waveguide, this may lead to a significant change in the properties of the transmitted field. Using Fresnel coefficients and including the effects of multiple reflections, one can derive the frequency-dependent transmission function

$$\tilde{T}(\omega) = \frac{\tilde{\alpha}(\omega)e^{ikL}}{1+\tilde{\beta}(\omega)e^{i2kL}}, \tag{7}$$

where

$$\tilde{\alpha}(\omega) = \frac{4n(\omega)}{(1+n(\omega))^2}, \tilde{\beta}(\omega) = -\frac{(1-n(\omega))^2}{(1+n(\omega))^2}, \tag{8}$$

and $k = \omega n(\omega)/c$ is the wavenumber in the waveguide.

Fig. 5 shows the field transmission and effective index for 200-μm-diameter waveguides calculated using Eq. (7). In the case of a 1-mm length waveguide, one can see oscillations in the transmission just above the cutoff frequency due to a Fabry–Perot effect. Eq. (7) can also reproduce an effective index that is negative at low frequencies. A negative index implies a wave that emerges from the waveguide before entering it. This bizarre effect, which has been observed very clearly in a very short waveguide [8], is strictly the result of phase shifts occurring on the boundary between the waveguide and air. Superluminal group velocities may only be observed when the waveguide is sufficiently long that the etalon effect for evanescent waves can be ignored.

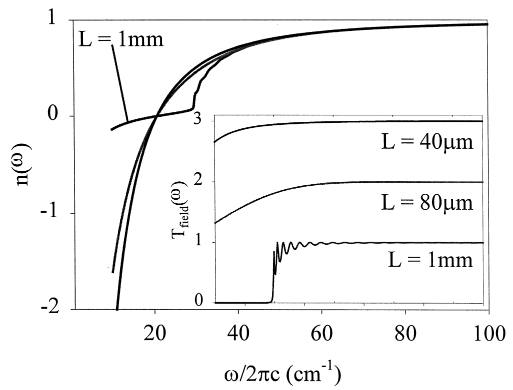

Fig. 5. Theoretical calculation of waveguide refractive index by including multiple reflections, for $d = 200$ μm and waveguide lengths $L = 40$, 80 and 1000 μm. (Inset) Calculated theoretical field transmission $|\tilde{E}(\omega)/\tilde{E}_0(\omega)|$ (the curves have been offset for clarity).

3. Discussion

Is it possible to transmit information superluminally and hence, in some inertial frames, to receive the information before it has been sent? If the device response is causal and its length is L, the output electric field is related to the input field by

$$E_{\mathrm{out}}(t) = \int_{-\infty}^{\infty} d\tau\, E_{\mathrm{in}}(t-\tau)\, r(\tau - L/c), \tag{9}$$

and the response function $r(t)$ is zero for $t < 0$. Any information transmitted at times $t < L/c$ would violate causality in some Lorentz frames. In the present case, the time-response function is found from the Fourier transform of Eq. (7). The effective index of the waveguide tends to 1 as the absolute value of the complex frequency tends to infinity. Therefore, the Fourier transform can be performed by contour integration by closing the contour in the upper-half plane (UHP) if $t - L/c < 0$. Therefore, the waveguide response is causal if there are no poles in the UHP of the integrand [16]. We have not been able to find an analytical expression for the position of the poles but a numerical search only resulted in poles in the LHP. As a further causality proof, the Fourier transform of

Eq. (7) was performed numerically. The first response of the system is a Dirac delta function arriving at $t = L/c$. Thus, electromagnetic-wave transmission through a waveguide is causal even when one includes the effect of multiple reflections of evanescent waves each traveling at infinite velocity.

Causality is often considered proof that superluminal communication is impossible. In some cases, the response function has such a form that it appears as if information is traveling superluminally. However, the tunneling device in effect performs an extrapolation into the future [6,11]. This has been demonstrated beautifully in experiments using resonant amplifiers in which the peak of the output pulse may leave the circuit before the peak of the input pulse arrives at the input port [17,18]. Such an extrapolation could be performed even for a pulse traveling through free space. Taylor expansion of the wing of a pulse arriving before the peak could be used to predict the arrival time of the peak. Thus, genuinely new information is contained in points of non-analyticity (the 'front') and these travel at the front-velocity, which is equal to the speed of light in vacuum [1,16]. This can be understood as arising from the fact that discontinuities have Fourier components at infinite frequency and in a waveguide these infinite frequency components would be above cutoff.

Time-domain signals containing points of non-analyticity have spectra falling off towards infinite frequency as ω^{-n}, where n is a positive integer whose value depends on the nature of the discontinuity. However, practical communication devices have a finite response time and are inherently noisy. Therefore, it is problematic to define information in terms of points of non-analyticity. In addition, extrapolation into the future using a Taylor expansion of the tail of a signal pulse has an inherent bit-error rate (BER), which grows larger the further one tries to extrapolate. In this particular sense, the principle of causality is irrelevant in deciding whether superluminal communication is possible or not. One 'bit' of information is received when the detector has received a sufficient number of photons to be sufficiently sure that an on-bit rather than an off-bit was received. In other words, a signal may be defined as a pulse (or some other shape) that a detector can distinguish from noise. This does not mean that information is defined simply by the peak of the pulse: the detector should be able to distinguish between on and off bits with acceptable S/N, which requires a finite amount of averaging time and a finite number of photons. Therefore, the question is whether one can receive a superluminal signal with a sufficiently low BER to make it a viable proposition.

Practical signals are never genuinely bandwidth limited either as suggested previously [12], if only because the communication device has to be switched on (and off), introducing a transient in the time domain. This transient may not be a point of non-analyticity but unavoidably, the spectrum of a signal will have wings extending to higher (or lower) frequencies. Any physically reasonable system must have a frequency above which the propagation speed is equal to the vacuum speed of light. Thus, the spectrum of any practical signal will have frequency components that travel at the speed of light or less and are unattenuated. At some travel distance, these subluminal components will become dominating. In all experimental 'demonstrations' of superluminal communication so far [12], the temporal advance made has always been less than the inverse bandwidth of the signal. This is a crucial point as can be demonstrated with a simple calculation. A 200-μm-diameter waveguide has a cutoff frequency of 29.3 cm^{-1}. A pulse with a bandwidth less than this cutoff will have a width of more than ~ 0.5 ps. According to the waveguide propagation expression, Eq. (4), a 150-μm length waveguide is required to advance the pulse by two pulse widths. For an advance ten times larger, the transmitted power would be 10^{-24}. Therefore, superluminal signal propagation would be possible if one could suppress the components above the cutoff frequency sufficiently. In a communication system that remains on without interruption and drift for $\sim 10^5$ years (10^{12} s), the transmitted evanescent waves have about the same power as the non-evanescent ones. To attain the communications industry standard BER of 10^{-9}, the communications system has to be stable for $\sim 10^8$ years. Thus, ignoring group-velocity dispersion, signals can be transmitted superluminally over 1.5 mm (gaining 5 ps) with a BER of 10^{-9} provided the message has a duration of 10^8 years. The attenuation of evanescent waves is astonishing and implies that any non-evanescent component, no matter how small, will always end up dominating the transmitted signal. This leads to the rather unsatisfactory conclusion that superluminal communication is possible but pointless as the message length must be much larger than the advance made.

Acknowledgements

We gratefully acknowledge financial support from the Royal Society and EPSRC, and technical support from A. Hughes. J.Z. gratefully acknowledges financial support from an Overseas Research Students Award Scheme.

References

[1] L. Brillouin, Wave Propagation and Group Velocity, Academic Press, New York, 1960.
[2] H.M. Brodowsky, W. Heitmann, G. Nimtz, Phys. Lett. A 222 (1996) 125.
[3] A. Enders, G. Nimtz, J. Phys. 3 (1993) 1089.
[4] S. Chu, S. Wong, Phys. Rev. Lett. 48 (1982) 738.
[5] C. Spielmann, R. Szipöcs, A. Stingl et al., Phys. Rev. Lett. 73 (1994) 2308.
[6] R.Y. Chiao, A.M. Steinberg, Prog. Opt. 37 (1997) 345.
[7] R. McElroy, K. Wynne, Phys. Rev. Lett. 79 (1997) 3078.
[8] K. Wynne, D.A. Jaroszynski, Opt. Lett. 24 (1999) 25.
[9] E. Pollak, W.H. Miller, Phys. Rev. Lett. 53 (1984) 115.
[10] P. Balcou, L. Dutriaux, Phys. Rev. Lett. 78 (1997) 851.
[11] A.M. Steinberg, S. Myrskog, H.S. Moon et al., Ann. Phys. (Leipzig) 7 (1998) 593.
[12] G. Nimtz, Eur. Phys. J. B 7 (1999) 523.
[13] S.Y. Liao, Microwave Circuit Analysis and Amplifier Design, Prentice-Hall, Englewood Cliffs, 1987.
[14] H.A. Bethe, Phys. Rev. 66 (1944) 163.
[15] T. Thio, H.F. Ghaemi, H.J. Lezec et al., J. Opt. Soc. Am. B 16 (1999) 1743.
[16] J.D. Jackson, Classical Electrodynamics, Wiley, New York, 1999.
[17] J.C. Garrison, M.W. Mitchell, R.Y. Chiao et al., Phys. Lett. A 245 (1998) 19.
[18] M.W. Mitchell, R.Y. Chiao, Phys. Lett. A 230 (1997) 133.