Antireflection coatings optimized for single-cycle THz pulses

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We show that a single-layer antireflection coating on a THz source of high refractive index can substantially increase the transmission of emitted THz pulses. Calculations indicate that the optimum coating thickness depends on the exact shape of the generated THz waveform and whether the transmitted waveform is to be optimized for the highest peak (temporal) amplitude, peak spectral amplitude, or pulse energy. We experimentally demonstrate a 15% increase in peak amplitude, a 33% increase in peak spectral amplitude, and a 48% increase in energy for a 100 μm thick fused silica AR coating on a lithium niobate crystal used as THz emitter. © 2013 Optical Society of America

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1. Introduction

The emitters and detectors most commonly used in THz time-domain spectroscopy have a high refractive index $n$ in the THz spectral range (ZnTe: $n = 3.2$ [1], GaP: $n = 3.3$ [2], GaAs: $n = 3.6$ [3], LiNbO$_3$: $n = 5.0$ [4]), which leads to a high reflectance $R = [(n - 1)/(n + 1)]^2$ of each of their surfaces (ZnTe: $R = 0.27$, GaP: $R = 0.29$, GaAs: $R = 0.32$, LiNbO$_3$: $R = 0.44$). The resulting strong secondary reflections often limit the length of the measurement time window and thus the spectral resolution. In order to increase the dynamic range and improve the resolution of a spectrometer, antireflection (AR) coatings for its source and detector crystals are highly desirable. AR coatings on emitter crystals would also be beneficial for nonlinear THz experiments since even a small increase in THz electric or magnetic field strength could potentially reduce the requirements for cost intensive laser systems [5].

Recently, a microstructure on silicon showing broadband AR properties at THz frequencies was demonstrated [6]. However, it might be difficult to fabricate such a structure on some of the important THz emitter and detector crystals, e.g., on organic nonlinear optical crystals [7–9]. Single-layer dielectric AR coatings have been developed for continuous THz waves or narrowband THz pulses [10–14]. In the visible and infrared spectral range, broadband dielectric AR coatings are typically composed of several tens to hundreds of alternating high and low refractive index layers (see, e.g., [15]). However, this design is inapplicable to single-cycle THz pulses for technical reasons. The overall coating would be extremely thick, difficult to fabricate, and potentially strongly scattering or absorbing.

In this paper, we demonstrate that a sufficiently broadband enhancement of the transmission can be achieved with a single-layer AR coating of appropriate thickness. We show that the optimum layer thickness depends on the parameter that is to be maximized, e.g., the peak (temporal) amplitude, peak spectral amplitude, or pulse energy. When maximizing the peak amplitude, the optimum thickness depends on the specific waveform and not only on the amplitude spectrum of the THz pulse. As an example, a lithium niobate crystal used as a source of...
intense single-cycle THz pulses was coated with a thin fused silica plate.

2. Calculation of the Optimum AR Coating Thickness for Single-Cycle THz Pulses

First, we consider a THz emitter with refractive index \( n \) coated with a layer of thickness \( d \) and refractive index \( n_c \). The refractive index of the ambient medium is \( n_0 = 1 \). The spectral electric field of the transmitted THz pulses \( \hat{E}_{\text{out}}(\nu) \) can be calculated from the transfer function \( H(\nu) \) and the Fourier spectrum of the pulses inside the emitter \( \hat{E}_{\text{in}}(\nu) \):

\[
\hat{E}_{\text{out}}(\nu) = H(\nu)\hat{E}_{\text{in}}(\nu),
\]

where \( \nu \) is the frequency. Absorption in the emitter and the coating layer are assumed to be negligible and thus the refractive indices are real. The transfer function \( H(\nu) \) for the single-layer AR coating can be written as

\[
H(\nu) = \frac{4nn_c \exp(-i\frac{2\pi n_n d}{c})}{(n_c + 1)(n + n_c) + (n_c - 1)(n - n_c)\exp(-i\frac{4\pi n n_c d}{c})}.
\]

(2)

The transmittance of the coated THz emitter is given by \( T(\nu) = |H(\nu)|^2/n \). Note that a THz detector with the same refractive index and AR coating as the THz emitter has the same transmittance \( T(\nu) \). The transmitted waveform \( E_{\text{out}}(t) \) can be calculated by the inverse Fourier transform of its spectrum \( \hat{E}_{\text{out}}(\nu) \) given by Eq. (1). If the dispersion of the emitter and the AR coating can be neglected, the waveform can be written as a superposition of the main pulse and its replicas

\[
E_{\text{out}}(t) = t_{n,n_c}t_{n_c,1} \sum_{k=0}^{\infty} r_{n_c,1}^k r_{n,n_c}^k E_{\text{in}}(t - k\Delta t),
\]

where \( \Delta t = 2dn_c/c \) is the time delay between the replicas, \( E_{\text{in}}(t) \) is the waveform inside the emitter, and \( t_{n,n_c} = 2n/(n + n_c) \), \( t_{n,1} = 2n_c/(n_c + 1) \), \( r_{n_c,1} = (n_c - 1)/(n_c + 1) \), and \( r_{n,n_c} = -(n - n_c)(n + n_c) \) are the Fresnel transmission and reflection coefficients, respectively. Two independent phenomena are responsible for the enhancement of the transmission due to a single-layer AR coating. On the one hand, the product of the Fresnel transmission coefficients of the coated substrate \( t_{n,n_c} t_{n_c,1} \) is larger than the Fresnel transmission coefficient of the uncoated substrate \( t_{n,1} \). On the other hand, the transmission is increased if the transmitted pulse interferes constructively with its replicas (see Fig. 1) or equivalently, the reflection losses are decreased if the reflected pulse interferes destructively with its replicas.

In the following, the optimization of the AR coating thickness with respect to different parameters is shown. As a reference, we first calculate the optimum coating thickness \( d_0 \) for the maximum peak spectral amplitude of the transmitted THz pulse. It is well known that an ideal transmittance of \( T(\nu_0) = 1 \) at the peak frequency \( \nu_0 \) is obtained if the AR coating has a refractive index of \( n_c = \sqrt{n} \) and a quarter wavelength optical thickness, i.e., \( d_0 = c/(4\nu_0 n_c) \), where \( c \) is the speed of light in vacuum. The spectral amplitude of the THz pulse is enhanced by a factor of \( \sqrt{T(\nu)/T_0} \), where \( T_0 = 4n(n + 1)^{-2} \) is the transmittance of the uncoated material.

For some applications, it might be desirable to optimize the thickness of the AR coating for the maximum energy of the transmitted THz pulse, in which case the optimum thickness maximizes \( \int_0^\infty |E_{\text{out}}(\nu)|^2 d\nu \).

Finally, high-field THz experiments benefit from the highest possible peak field strength within the THz waveform. For a single-layer AR coating, the highest peak amplitude of the transmitted THz pulse is achieved if the time delay between the transmitted pulse and its first replica corresponds to the time difference between the maximum and the preceding minimum of the main pulse. In this case, the optimum thickness of the AR coating depends on the exact shape of the single-cycle waveform. For example, quasi-unipolar or bipolar single-cycle THz pulses can be generated both in photo conductive antennas \[16\] and in nonlinear optical crystals \[8,9\]. For the following discussion, we use idealized unipolar and bipolar waveforms described by the second and first derivatives of a Gaussian function with the full width at half-maximum of \( 2\sqrt{\ln 2}\tau \).
\[ E_{\text{unipolar}}(t) = E_0 \exp \left( -\frac{t^2}{\tau^2} \right) \left( 1 - 2 \frac{t^2}{\tau^2} \right) \] (4)

and

\[ E_{\text{bipolar}}(t) = E_0 \sqrt{2} \exp \left( \frac{1}{2} - \frac{t^2}{\tau^2} \right) \frac{t}{\tau} \] (5)

where \( E_0 \) is the peak amplitude. The constructive interference of these waveforms with their first replicas generated in LiNbO\(_3\) with a fused silica AR coating \((n_c = 1.95 [3])\) is illustrated in Fig. 1. For both the unipolar [Fig. 1(a)] and the bipolar [Fig. 1(b)] waveform, the thickness of the AR coating is chosen such that the maximum amplitude of the first replica, which is inverted due to the internal reflections, temporally coincides with the maximum of the transmitted waveform.

The enhancement factors for the peak spectral amplitude, the transmitted pulse energy, and the peak amplitude as functions of the coating thickness are shown in Fig. 2. The thickness is normalized to the quarter wavelength optical thickness \(d_0\) at the peak frequency \(\nu_0\). The maximum enhancement factors and the corresponding optimum thicknesses are indicated in the figure. Note that the peak field strengths can be enhanced by as much as 21\% and 30\% for uni- and bipolar pulses if the coating thickness is reduced to 0.78\(d_0\) and 0.64\(d_0\).

3. Experiments

For an experimental demonstration of the performance of a single-layer AR coating, we generated high-field quasi-unipolar THz pulses through optical rectification of femtosecond laser pulses with a tilted pulse front in a LiNbO\(_3\) crystal [17]. The THz waveforms transmitted into air were measured using electro-optic sampling in a 1 mm thick ZnTe crystal. The waveforms were recorded for an uncoated LiNbO\(_3\) crystal and a LiNbO\(_3\) crystal coated with a 100 \(\mu\)m thick fused silica plate under identical conditions. The optimum fused silica layer thicknesses for the measured waveform would have been 92 and 112 \(\mu\)m for the highest peak amplitude and peak spectral amplitude, respectively. We found a 1.15 times higher peak amplitude, a 1.33 times higher peak spectral amplitude, and a 1.48 times higher pulse energy with the coated emitter. That is, the reflection losses of the AR coated surface were reduced to 40\% of the reflection losses of the uncoated surface.

The expected THz signal in the frequency- and time-domain emitted from the coated crystal was calculated with the measured THz signal from the uncoated crystal using Eqs. (1) and (3), respectively (see Fig. 3). We find a good agreement between the expected and measured THz signals.

![Fig. 2. Fused silica AR coating on a LiNbO\(_3\) substrate: enhancement factors for peak spectral amplitude (solid line), peak amplitude (dotted line), and energy (dashed line) of (a) a unipolar and (b) bipolar THz pulse as functions of the coating thickness.](image)

![Fig. 3. THz pulses emitted from a LiNbO\(_3\) crystal coated with a 100 \(\mu\)m thick fused silica plate (solid line) and from an uncoated LiNbO\(_3\) crystal under identical conditions (dashed line). (a) The measured THz transients and (b) the corresponding spectra. The expected THz signal from the coated crystal calculated with the measured THz signal from the uncoated crystal using Eqs. (1) and (3), respectively (dotted line).](image)
4. Conclusion

We showed that a single-layer AR coating can substantially increase the peak amplitude of single-cycle THz pulses, which is highly beneficial for high-field THz experiments. Moreover, the calculations indicate that the AR coating thickness not only varies considerably if optimized for the highest peak spectral amplitude, the highest peak amplitude, or the highest THz pulse energy but also depends on the exact shape of the THz waveform. As an important example, we experimentally demonstrated a 15% increase of the peak amplitude for a fused silica AR coating on a LiNbO$_3$ crystal. The optimization procedures described in this article can be easily extended from single- to few-layer AR coatings.

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References


