Free-space terminator and coherent broadband blackbody interferometry

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Received August 11, 2005; revised September 24, 2005; accepted September 25, 2005

We propose a free-space terminator and broadband interferometry based on a coherent blackbody effect in an ultrathin nonreflecting metallic layer in the microwave to infrared domains. A frequency-insensitive device consisting of a metallic layer in a ring (Sagnac) interferometer can be used for autocorrelation measurements of extremely broad EM spectra. © 2006 Optical Society of America

OCIS codes: 310.6860, 260.3910, 260.3160, 350.4010.

In waveguides or transmission lines, the full absorption of incident waves is achieved by using a terminator with impedance matching that of the guiding structure. No such broadband terminator exists for free space. In this Letter we demonstrate that a terminator or blackbody (BB) can be designed that would be insensitive to the frequency of radiation in an extremely broad domain; the terminator may also serve as a coherent broadband interferometer. The proposed device is based on an extremely thin metallic film or other highly absorbing layer and might be of great interest for many applications.

As was shown in Ref. 1, an EM wave that is normally incident on a thin metallic film whose thickness d is much smaller than its skin depth, $\delta = c/\sqrt{2\pi\sigma\omega}$, where σ is the dc conductivity of the metal (in Gaussian units, σ has dimensions $[s^{-1}]$), has reflectivity R, transmittivity T, and absorption A, as

$$R = \left(1 + \frac{h}{d}\right)^{-2}, \quad T = \left(1 + \frac{d}{h}\right)^{-2}, \quad A = 1 - R - T, \tag{1}$$

where $h = c/2\pi\sigma = 2\pi\delta^2/\lambda$ is a characteristic spatial scale; for good metals (e.g., Au, Ag, Al, Cp) h is orders of magnitude smaller than δ and corresponds to 10–20 atomic layers.[1] At $d=h$, the absorption reaches its maximum, $A=1/2$. The respective resistance per square is $(h\sigma)^{-1} = 2\pi/c = Z_{\mathrm{vac}}/2$, where $Z_{\mathrm{vac}} = 4\pi/c$ is the impedance of vacuum in electrostatic units; i.e., the maximum A is attained when the resistance of a film matches the half-impedance of vacuum (188.5 Ω). This remains the case from the rf to the sub-mm domain. Since the mean free path of electrons in an ultrathin layer reduces almost to the thickness of that layer, these results are valid up to midinfrared.[1] Early[2–4] and recent[5,6] experiments have confirmed this phenomenon; applications to the visualization of microwave modes,[7–9] broadband spectroscopy,[10–12] and photon crystals[13,14] have been developed. $A=0.5$ is a large absorption value (compared with a thick layer with $1-R \sim A \ll 1$), but it is still not 100%. Yet, one can make a structure with $d=h$ work in a 100% absorption mode. Let us immerse such a layer into an (initially) standing EM wave formed by two waves counterpropagating normally to the layer. Since the amplitude reflection coefficient is $r = -|\sqrt{R}| = -d/(h+d)$, the reflection of a straight-propagating (+) incident wave of the unity amplitude at $d=h$ will form a backpropagating wave, $E_{\mathrm{refl}}^{(+)}$ with the amplitude −0.5. At the same time, if a backpropagating (−) incident wave has exactly the same phase at the film as the + incident wave, its transmitted portion, $E_{\mathrm{trans}}^{(-)}$, will have the same phase, $t = |\sqrt{T}| = h/(h+d)$, and $t=0.5$, so that $E_{\mathrm{refl}}^{(+)} = -E_{\mathrm{trans}}^{(-)}$, and similarly, $E_{\mathrm{refl}}^{(-)} = -E_{\mathrm{trans}}^{(+)}$. Thus, there will be no waves going away from the film in any direction, and the energy of both incident waves will be fully absorbed. Such an arrangement corresponds to the maximum of the electric field of the original standing wave coinciding with the film, and the largest absorption is due to the largest generated electrical current. When the position of the film coincides with the node of the original standing wave, where the electrical field vanishes, the absorption vanishes, too. A similar effect would exist in a coaxial cable or waveguide.

An experimental device can be realized as a ring (Sagnac) interferometer (Fig. 1) in which a single incident wave is split into two waves of equal intensity, which are then sent on a collision course with the thin metallic film normal to the line of their propagation. If the film coincides with an antinode of the standing wave, the wave energy will be fully absorbed, with no reflection from the device, whereas if the film coincides with a node, there will be a full reflection. For a monochromatic wave with frequency ω and wave number $k=\omega/c$, the BB reflection, $R^{(\mathrm{BB})}$ normalized to that of the system without the absorbing layer, versus the distance x of the layer from the exact center of the interferometer, is

$$R^{(\mathrm{BB})} = \sin^2(xk) = \sin^2(\omega\tau/2), \tag{2}$$

where $\tau = 2x/c$. For an arbitrary incident temporal profile, $E(t)$ with $\int_{-\infty}^{\infty} E(t)\mathrm{d}t = 0$, with a normalized autocorrelation function, $F(\tau) = \langle E(t)E(t-\tau)\rangle / \langle E^2(t)\rangle$, where the angle brackets $\langle\ \rangle$ stand for averaging over

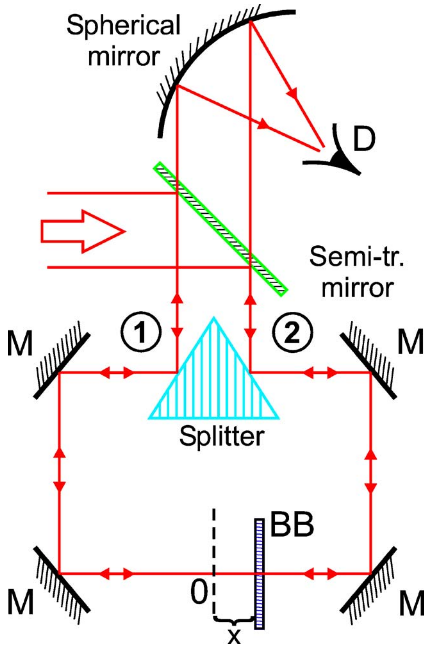

Fig. 1. (Color online) Ring (Sagnac) interferometer using a thin metallic film BB. M, metallic mirror; D, intensity detector.

time, $\langle\zeta\rangle=\int_{-t_{av}}^{t_{av}}\zeta dt/2t_{av}$ as $t_{av}\to\infty$ $[F(\tau)=F(-\tau)]$, the spectrum is

$$S(\omega)=\frac{1}{\pi}\int_0^\infty F(\tau)\cos(\omega\tau)d\tau. \quad (3)$$

Suppose that we shut down one of the outputs, e.g., channel 2, behind the semi-transparent mirror (Fig. 1). The output in channel 1, E_{1out}, is then formed by input 2, E_{2in}, which passes through the loop without a change of sign and is attenuated by a factor of 2, and by input 1, $E_{1in}=E_{2in}$, which is reflected by a thin film with the same attenuation but changes its sign so that

$$E_{1out}(\tau)\propto E_{in}(\tilde{t})-E_{in}(\tilde{t}-\tau), \quad (4)$$

where $\tilde{t}=t-t_0$ and $t_0=L/c$ is a time delay over the full ring of length L. The normalized BB reflection at a fixed delay τ is then $R_1^{(BB)}(\tau)=\langle E_{1out}^2(\tau)\rangle/4\langle E_{in}^2(0)\rangle$. Using Eq. (4), and keeping in mind that, due to Eq. (3), $F(\tau)=2\int_0^\infty S(\omega)\cos(\omega\tau)d\omega$, and $F(0)=2\int_0^\infty S(\omega)d\omega=1$, we have

$$R_1^{(BB)}(\tau)=\frac{1-F(\tau)}{2}=2\int_0^\infty S(\omega)\sin^2\left(\frac{\omega\tau}{2}\right)d\omega. \quad (5)$$

Note that $R_1^{(BB)}(0)=0$, $R_1^{(BB)}(\tau)=O(\tau^2)$ as $\tau\to 0$, and, for $F(\infty)=0$, we have $R_1^{(BB)}(\infty)=1/2$. As a typical example, consider a Gaussian intensity spectrum, $S(\omega)$, with an arbitrary bandwidth $\Delta\omega$ centered around some frequency ω_0:

$$S(\omega)=[\exp(-s_+^2)+\exp(-s_-^2)](2\Delta\omega\sqrt{\pi})^{-1}, \quad (6)$$

where $s_\pm=(\omega\pm\omega_0)/\Delta\omega$. The total intensity reflectivity is then evaluated as

$$R_1^{(BB)}(\tau)=[1-\cos(\omega_0\tau)X]/2, \quad (7)$$

where $X=\exp[-(\tau\Delta\omega/2)^2]$, which coincides with Eq. (2) if $\Delta\omega\to 0$. When both output channels are opened, so that the full output signal is $E_{out}(\tau)\propto E_{in}(\tilde{t})-(1/2)\times[E_{in}(\tilde{t}-\tau)+E_{in}(\tilde{t}+\tau)]$, similarly to the case of Eq. (5), we obtain for the BB reflection $R_\Sigma^{(BB)}(\tau)=[3-4F(\tau)+F(2\tau)]/8$, or

$$R_\Sigma^{(BB)}(\tau)=2\int_0^\infty S(\omega)\sin^4\left(\frac{\omega\tau}{2}\right)d\omega. \quad (8)$$

For a Gaussian spectrum [Eq. (6)] we have [compare with Eq. (7)]:

$$R_\Sigma^{(BB)}(\tau)=8^{-1}[3-4\cos(\omega_0\tau)X+\cos(2\omega_0\tau)X^4]. \quad (9)$$

For monochromatic input, $\Delta\omega=0$, we have $R_\Sigma^{(BB)}=\sin^4(\omega_0\tau/2)$. In the case of whitelike noise, $\Delta\omega\gg\omega_0$, Eqs. (7) and (9) reduce to $R_1^{(BB)}(\tau)=(1-X)/2$, and

$$R_\Sigma^{(BB)}(\tau)=(1-X)^2(3+2X+X^2)/8, \quad (10)$$

respectively. At $\tau\Delta\omega\equiv q\ll 1$, we have $R_1^{(BB)}(\tau)\approx q^2/8$, while $R_\Sigma^{(BB)}(\tau)\approx q^4(3/64)$; i.e., a double-channel arrangement is much more sensitive to the high-frequency details of the spectrum. Using simultaneous autocorrelation at two different delay times, τ and 2τ, may substantially enhance the resolution of this interferometry. Figure 2 depicts R versus $\omega_0\tau$ for various ratios $\Delta\omega/\omega_0$ for both channels opened.

To measure signals with a superbroad spectrum, all the mirrors in the interferometer (Fig. 1) should be metallic, and the semi-transparent mirror should also be made from a very thin metallic layer to rule out any resonant or frequency-sensitive effects that may occur if the mirrors are made from dielectric layers.

This kind of device is well suited for terahertz technology; other applications may include the detection of high-frequency coherent features for detecting information transmission in a pseudo-white-noise signal and potentially for detecting extraterrestrial signals and primordial radiation in the microwave domain. The important factor is that BB interferometry generates zero output at $\tau=0$, which may greatly

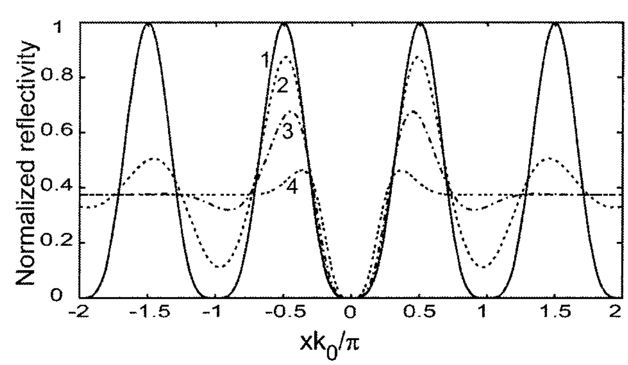

Fig. 2. Normalized refractivity of the interferometer versus normalized BB position, $xk_0/\pi=\tau\omega_0/2\pi$, for the broad-spectrum signal (6), for both channels. Curves: 1, $\Delta\omega=0$; 2, $\Delta\omega=\omega_0/4$; 3, $\Delta\omega=\omega_0/2$; 4, $\Delta\omega=\omega_0$.

increase its sensitivity compared with that of regular autocorrelation, whereby the autocorrelation signal at small delay times τ is finite. For applications such as detection of primordial radiation, special care should be taken with BB radiation from the BB element (as with the other mirrors); it should be cooled using, e.g., liquid helium. The BB radiation may become an unwanted nonlinear effect if it is sufficiently strong to heat the BB element, in which case the BB may be cooled by, e.g., liquid nitrogen.

For a narrowband signal, further enhancement may be attained by employing more than one metallic layer and the ensuing resonances.[13,14] For monochromatic radiation with wavelength λ, if the spacing between layers with $A=1/2$ is $\lambda/2$, the system is fully transparent, if it is irradiated again from both directions. Conversely, a reflection resonance would exist if the spacing is $\lambda/4$, whereby the amplitude of reflection of each of the waves is $r=-2/5$, and the transmission is $t=1/5$. If the couple is positioned strictly at the center of the ring interferometer, $r=-1/5$, and thus $R=4\%$, the system has substantial frequency selectivity. A natural extension of the BB interferometer is to use fiber optics.

In conclusion, a broad-frequency free-space nonreflective element and coherent blackbody interferometry based on an ultrathin metallic layer have been incorporated into a ring (Sagnac) interferometer that has been shown to be a promising tool for absorbing and analyzing extremely broad-spectrum radiation in the radio to mid-infrared domain.

This work is supported by the U.S. Air Force Office of Scientific Research. A. E. Kaplan's e-mail address is sasha@striky.ece.jhu.edu.

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