Enhanced Laser-Light Absorption by Optical Resonance in Inhomogeneous Plasma*

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(Received 26 December 1972)

The collisional absorption of laser radiation by a planar plasma was calculated using the classical physical optics of absorbing media. In most regions of interest to thermonuclear fusion, the enhanced absorption of p-polarized radiation by optical resonance—particularly at high temperatures and long laser wavelength—completely dominates the ordinary absorption due to inverse bremsstrahlung.

Questions concerning the efficiency of heating dense plasma by laser irradiation, particularly at widely different wavelengths, are of considerable current interest. This communication considers only collisional absorption, and presents some results of calculations which indicate that, contrary to the present consensus, absorption by inverse bremsstrahlung is important at all temperatures and intensities of interest to thermonuclear fusion. This surprising result is caused by enhancement of the absorption, due to an optical resonance effect, which is found to be markedly important at high temperatures and long wavelengths.

The prediction of an enhancement of power absorption by means of optical resonance arises simply from using Maxwell's equations to calculate the reflectance of an inhomogeneous medium so constituted that the index of refraction vanishes at some depth. When the electric field of obliquely incident radiation is in the plane of incidence (p polarization), a nonzero longitudinal component of the electric field exists and is amplified into a damped singularity[1] at the critical surface where the index of refraction vanishes. In a plasma, this critical surface occurs where the frequency of Langmuir oscillations ω_p equals the frequency ω of the incident radiation.

The first physically consistent treatment of optical resonance fields in plasmas appears to have been given by Denisov.[1] The analysis was extended to the computation of power absorptance by Piliya,[2] and applied specifically to laser-generated plasmas by Vinogradov and Pustovalov.[3] These approximate analytical solutions are valid in the collisionless domain, as is the numerical solution of Freidberg *et al.*[4] Godwin[5] introduced a simple approximate analytical solution of a restricted two-layer model (with small, but unspecified, damping) based on the well-understood optical resonance in thin metal films. Bachynski and Gibbs,[6] using microwave probes within a slab of plasma, have experimentally corroborated the theory of Denisov for longitudinal electric fields at resonance.

Nevertheless, the question of optical resonance absorption with a plasma of realistic density profile in the collision-dominated regime remains outstanding and forms the subject of this investigation. In this work, the reflection of p-polarized radiation from an inhomogeneous isotropic plasma is calculated by considering the plasma to be composed of a large number of parallel homogeneous layers. The complex permittivity within each layer is computed at an assumed constant effective electron temperature by considering only the inverse bremsstrahlung (free-free) absorption mechanism. Then the reflectance, including all multiple reflections, of the array of plane-parallel stratifications is calculated by means of the classical physical optics of absorbing media.[7]

After the specification of the damping factor (the imaginary part of the permittivity) for each layer, the reflectance calculation for a given array of layers proceeds without approximation. However, a practical choice regarding the number of layers to be used must be made on the basis of parameter values, desired accuracy, and available computer time. When only a few layers are used, the curves of absorptance versus angle of incidence are quite sensitive to the number and spacing of the layers. However, as the number of layers exceeds about fifty, the shape of the absorptance curves becomes much less sensitive, and the change of shape becomes smaller as the number of layers increases. In the work reported here, the number of layers employed in the calculations varied from about 150 at small plasma thickness to 1700 at large plasma thickness, depending on the parameter values.

For simplicity of presentation, the calculations reported here assume a constant effective electron temperature and a linear rise of electron density from vacuum to the critical density. The overdense (supercritical) electron density is assumed to rise exponentially to that of the solid hydrogen target, but since wave penetration into the overdense region is limited, the assumed shape is of little importance. If we call the distance (in free-space wavelengths λ_0) from vacuum to critical density L; then, according to this assumed exponential profile, the total plasma thickness is $L\ (1+\ln N_s/N_c)$, where N_s and N_c are the electron densities at the solid and at the critical density.

Fidone[8] and Shearer,[9] also assuming this macroscopic model for the underdense region, have calculated the reflectance in closed analytical form utilizing refraction in the geometrical optical limit. The result is simply $\exp(-2s\cos^5\varphi)$, where s is the optical thickness of the underdense region at normal incidence, and φ is the angle of incidence of the incident radiation. In regions where there is no optical resonance, the present calculations agree with the expression of Fidone and Shearer precisely for $L \gtrsim 5\lambda_0$, approximately down to about $L=\lambda_0$, and depart significantly for $L \lesssim 0.5\lambda_0$. This comparison in the nonresonant regions serves as a check on the wave-optical method used here and also indicates where the geometrical-optical approximation becomes invalid.

The imaginary part of the permittivity for each homogeneous layer is given by $\epsilon_1 = \nu\omega_p^2/\omega^3$ where ν is the effective electron-ion collision frequency determined, at low radiation intensity and for a Maxwellian electron distribution, by the formula of Spitzer.[10] For very high intensities, at which the directed kinetic energy of oscillation per electron exceeds the random thermal energy, we use the theoretical results of Silin[11] and Bunkin and Kazakov.[12] We assume that the mean electron energy is constant throughout the underdense region. Because of the effectiveness of electron thermal conduction,[13] the assumption seems reasonable in the context of this work.

Some of the calculated results for hydrogen plasmas are displayed as computer-generated perspective plots of absorptance versus φ and L in Fig. 1. Plots (a), (b), (d), and (e) are based on the Spitzer model, while plots (c) and (f) are based on the Silin-Bunkin model at intensities of 10^{18} and 3×10^{15} W/cm^2, respectively.

As an example of the relationship between exponential absorption and optical resonance absorption, consider Fig. 1(a). From the absorption trough on the L axis ($L \simeq 20$) to large values of L, one sees a steeply-rising sheet of Fidone-Shearer absorption, perturbed by optical resonance only at small angles of incidence. For $L \leq 50$, ordinary absorption is negligible and optical resonance absorption is seen as a pronounced ridge heading toward larger angles as L decreases.

Note that optical resonance absorption dominates the ordinary absorption in most of parameter space above 1 keV for 1 μm, and above 0.1 keV for 10 μm. Because of optical resonance, CO_2 radiation is absorbed as effectively as Nd :glass radiation—the main difference being markly reduced nonresonant absorption and the shift of the optical-resonance ridge to smaller angles of incidence for the CO_2 radiation. In either case, it is usually possible to find some realistic combination of parameters that will provide an absorptance greater than 50%.

These plots are best regarded as applying to one instant from the time history of a laser pulse (including prepulse). During the pulse, T_e necessarily increases and L usually increases so that the integrated absorptance would cover a large region of parameter space. Obviously, to calculate the integrated absorptance of a laser pulse, one needs to meld this absorptance calculation into a hydrodynamic expansion code. Nevertheless, as an order-of-magnitude guide (ignoring prepulses), L values of 100 for Nd:glass and 5 for CO_2 correspond roughly to 1-nsec pulse duration.

For intensities beyond the Spitzer regime, the ordinary absorption quickly becomes negligible and the optical-resonance ridge slowly becomes narrower, higher, and shifts to small angles as the mean electron energy increases. The absorptance at near-relativistic intensities is illustrated by plots (c) and (f), for which the mean electron energies are roughly 70 and 20 keV, respectively. At these intensities the peak absorptance is nearly 100% at about 1 deg angle of incidence. At intensities 3 times larger than those for plots (c) and (f), the peak absorptances decline to about 50% because the electron-ion collisions are now too infrequent.

Since this work assumes plane waves incident on a one-dimensionally inhomogeneous medium, the results should be applied with caution to real situations involving converging wave fronts and three-dimensional target plasmas. Strongly convergent wave fronts from short–focal-length lenses cause partial depolarization in the focal zone, and can give rise to an appreciable longitudinal component of electric field even with s-polarized incident radiation.[14] Thus, for example, one

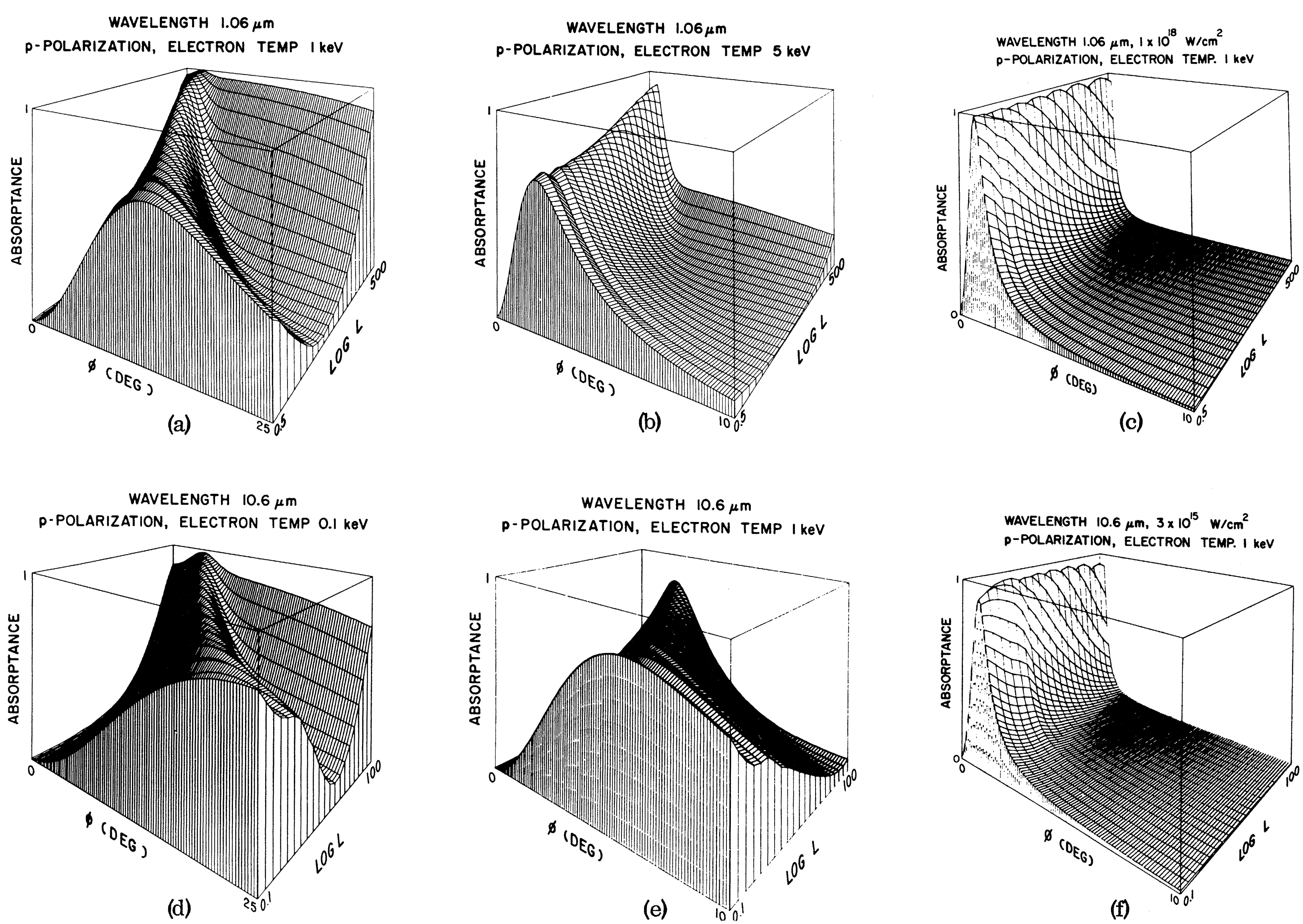

FIG. 1. Absorptance as a function of angle of incidence φ and underdense plasma depth L (in vacuum wavelengths) with laser wavelength, effective electron temperature, and beam intensity as parameters. Plots (a), (b), and (c) refer to Nd:glass laser radiation at 1.06 μm; while plots (d), (e), and (f) refer to CO_2 laser radiation at 10.6 μm.

might expect appreciable optical resonance when s-polarized light is incident through an $f/1$ lens.

Other microscopic plasma models (based on instability absorption, for example) could be used to calculate the damping factor in addition to the inverse bremsstrahlung model employed here. Indeed, there appear to be a score or more of absorption mechanisms which could, particularly at high intensity, contribute to the damping factor.

What is intended here is to demonstrate heuristically the importance of optical resonance absorption in simple, but reasonably realistic, circumstances. To the extent that future work can provide an exact and complete description of the damping factor as a function of location and time, the approach described here could then provide a reasonably accurate calculation of the absorption of radiant energy by a plasma.

I wish to thank Robert Godwin and Gene McCall for valuable discussions and encouragement. In particular, I am indebted to Dr. Godwin for considerable assistance in the early stages of this work.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] N. G. Denisov, Zh. Eksp. Teor. Fiz. 31, 609 (1956) [Sov. Phys. JETP 4, 544 (1957)]. See also V. L. Ginsburg, *Propagation of Electromagnetic Waves in Plasmas* (Pergamon, New York, 1970), p. 260 ff.

[2] A. D. Piliya, Zh. Tekh. Fiz. 36, 818 (1966) [Sov. Phys. Tech. Phys. 11, 609 (1966)].

[3] A. V. Vinogradov and V. V. Pustavalov, Pis'ma Zh. Eksp. Teor. Fiz. 13, 317 (1971) [JETP Lett. 13, 226 (1971)].

[4] J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. I. Rudsinski, Phys. Rev. Lett. 28, 795 (1972).

[5] R. P. Godwin, Phys. Rev. Lett. 28, 85 (1972).

[6] M. P. Bachynski and B. W. Gibbs, Can. J. Phys. 49, 3221 (1971).

[7] H. Wolter, in *Handbuch der Physik,* edited by S. Flügge (Springer, Berlin, 1956), Vol. 24, p. 461.

[8] I. Fidone, Nuovo Cimento 30, 666 (1963).

[9] J. W. Shearer, Phys. Fluids 14, 183 (1971).

[10] L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Interscience, New York, 1962), Chap. 5.

[11] V. P. Silin, Zh. Eksp. Teor. Fiz. 47, 2254 (1964) [Sov. Phys. JETP 20, 1510 (1965)].

[12] F. V. Bunkin and A. E. Kazakov, Zh. Eksp. Teor. Fiz. 59, 2233 (1970) [Sov. Phys. JETP 32, 1208 (1971)].

[13] J. W. Shearer and W. S. Barnes, Phys. Rev. Lett. 24, 92 (1970).

[14] A. Boivin and E. Wolf, Phys. Rev. 138, B1561 (1965).

Light Scattering from Weakly Ionized Nonhomogeneous Plasmas

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(Received 8 February 1973)

Rayleigh scattering is used to obtain the radial gas density and temperature distributions in low-current Ar arcs. A comparison with spectroscopic results indicates large deviations from local thermodynamic equilibrium. The possibilities of determining excited-state density distributions and transition probabilities by Rayleigh scattering are indicated.

The use of light scattering as a diagnostic tool for ionized gases has been confined, so far, chiefly to Thomson scattering by plasmas with a high degree of ionization.[1] Only recently were other applications reported like resonant[2] and near-resonant[3] Rayleigh and vibrational[4] and stimulated[5] Raman scattering.

In this Letter, nonresonant Rayleigh scattering is used as a new technique for determining gas temperatures and densities in nonhomogeneous weakly ionized plasmas. The method is applied to Ar arcs, of length 40 mm, which burn vertically in a quartz tube with inner and outer diameters of 16 and 20 mm, respectively. The cathode is a heated filament; heating is helpful for stabilizing the arcs, which are constricted.

The light-scattering apparatus is schematically shown in Fig. 1. Use of a pulsed non-Q-spoiled ruby laser, giving 0.5 J within 0.34 msec, made the scattered light intensity I_{sc} large enough to be discriminated from the background light of the discharge, while plasma heating is negligible. The intensity of stray light at the laser wavelength was reduced to 0.2% of I_{sc} for 1 atm Ar at room temperature by taking the following precautions: (i) A cylindrical section of height 5.4 mm is cut out from the middle of the tube, to avoid stray light from the quartz wall; (ii) the windows, which have a double antireflection coating, are placed sufficiently far from the scatter-