Letters

Development of Megawatt-Level Narrow-Band Far-Infrared Lasers for Plasma Diagnostics

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Abstract—**Required megawatt-level 30-MHz linewidth 496-μm radiation for plasma diagnostics may be achieved in CH_3F using an oscillator–pulse–amplifier combination employing transverse optical pumping (TOP). It is estimated that an upper limit of 150 J of CO_2 laser pump energy is required to produce 1-MW (0.07-J 60-ns) far-infrared (FIR) pulses.**

Interest has developed recently [1] in the use of submillimeter lasers for plasma diagnostics, particularly for Thomson scattering experiments where megawatt-level pulses of 30–100-ns duration and linewidth < 30 MHz are required. In this letter we propose to meet these requirements using an optically pumped methyl fluoride laser oscillator–amplifier combination at 496 μm.

Presently available kilowatt-level superradiant lasers [2] have such undesirable output characteristics [3] that the possibility of scaling these to megawatt levels without modification is unattractive. In particular, the linewidth is large ($\sim$700 MHz), the pulse shape irregular, and emission occurs simultaneously on a number of strong lines. However, by transverse optical pumping (TOP) of a conventional laser cavity it is possible [3] to produce kilowatt-level pulses which are smooth and adequately monochromatic. It should be possible therefore to meet the requirements of plasma diagnostics by amplifying the output of such a TOP laser to the megawatt level. An alternative approach, that of constructing a single large TOP laser, appears less favorable because of the possible excitation of undesirable parasitic modes (from wall reflections, etc.) in the very high-gain medium.

An estimate of the output energy of such an oscillator–amplifier combination may be made using a development similar to that already given for ruby laser [4] and CO_2 laser [5] amplifiers. The rate equations expressing energy and ion conservation are

$$\frac{\partial n(x,t)}{\partial t} = \sigma c n(x,t)\Delta N(x,t) - c\frac{\partial n(x,t)}{\partial x} \tag{1}$$

$$\frac{\partial \Delta N(x,t)}{\partial t} = -2\sigma c n(x,t)\Delta N(x,t) - \Delta N(x,t)/\tau_R \tag{2}$$

where $n(x,t)$ is the photon density in the pulse amplified along a distance x, $\Delta N(x,t)$ is the population inversion density, σ the stimulated emission cross section of the far-infrared (FIR) transition, τ_R the rotational relaxation time, and c the velocity of light. For input power $\sim$ 1 kW we have that $2\sigma c n(x,t) \gg 1/\tau_R$ so that the relaxation term $\Delta N(x,t)/\tau_R$ may be ignored. A lossless amplifier is also assumed. Equations (1) and (2) then yield

$$\frac{\partial E(x)}{\partial x} = \frac{\Delta N(0)}{2}\left[1 - e^{-2\sigma E(x)}\right] \tag{3}$$

for the increase in photon flux, $E(x)$ (photons/cm^2) at initial inversion density $\Delta N(0)$. The solution of (3) is

$$E_{\text{out}} = E_s \ln\left\{\left[\exp\frac{E_{\text{in}}}{E_s} - 1\right]\exp g_0 L + 1\right\} \tag{4}$$

where

E_{out} output pulse energy flux (J/cm^2);
E_{in} input pulse energy flux (J)cm^2);
E_s $=\hbar\omega/2\sigma$ is a saturation parameter;
g_0 $=\sigma\Delta N(0)$ = small signal gain at $\Delta N(0)$;
L amplifier length.

When $g_0 L \gg 1$ and $E_{\text{in}}/E_s \equiv \sigma E_{\text{in}}/\hbar\omega \gtrsim 1$, as is the case for a kilowatt-level oscillator driving a 1-m-long CH_3F amplifier, (4) becomes

$$E_{\text{out}} = E_s g_0 L \tag{5a}$$

$$E_{\text{out}} = \hbar\omega\frac{\Delta N(0)}{2}L. \tag{5b}$$

Equations (5) may be used to estimate the FIR output energy by assuming that $\Delta N(0)$ represents complete inversion of the FIR transition, i.e., that one half of the molecules of the gas have been pumped to the upper FIR laser level and that the lower laser level is empty. At a pressure of 2 torr and L = 1 m (5) then give $E_{\text{out}} = 1.4 \times 10^{-3}$ J/cm^2. If the amplified beam has an area of 50 cm^2 and pulses are typically 60-ns long, the output is 0.07 J/pulse with peak power $\sim$ 1 MW. This estimate may also be reached by noting that (5a) can be written $E_{\text{out}} = \hbar\omega(g_0/2\sigma)L$ where σ can be calculated using the known [6] value of the spontaneous relaxation time (2.3 $\times$ 10^2 s) and g_0 has been measured approximately for superradiant lasers. For $g_0 \sim 40$ dBm^{-1} and $\sigma = 2.2 \times 10^{-15}$ cm^2 we again get $E_{\text{out}} = 10^{-3}$ J/cm^2. Numerical agreement between the two methods of estimating E_{out} implies that indeed $\Delta N(0)$ represents inversion of half the gas molecules. Thus rotational relaxation within the lower vibrational state is sufficiently rapid to allow all molecules to enter the lower level of the pumping transition and thus to contribute to the FIR output.

Before estimating the pumping requirements, it is important to recognize that (5) applies only to a single FIR transition whereas actually several transitions (K = 1 through K = 7) are observed [2] in the output of superradiant lasers. It is possible, therefore, that pump energy may be wasted in noncontributing transitions. However, since the FIR transition is homogeneously broadened, all K values will in fact contribute provided that the inequalities leading to (5) continue to hold. This will occur as long as the Lorentz factor contained in g_0 and in σ is not too small. We estimate that K lines separated as far away as about 600 MHz from the oscillator frequency will still contribute fully to the output. This also implies that, if the TOP-laser oscillator can be made tunable to this extent, a tuning range of about 600 MHz at megawatt-power levels will become possible.

The pumping energy W_p which is required for megawatt-level FIR pulses is then bracketed by the theoretical quantum efficiency (1 percent) on the one hand, and the efficiency which we observe empirically (0.5 $\times$ 10^{-3}) for nonoptimum conditions (superradiant laser) on the other. We thus find 7 J < W_p < 150 J. In setting this upper limit we assume that efficiency is not affected by an increase in pumping energy density which in fact goes from 1 J/l for the superradiant case to 30 J/l under present circumstances. This assumption seems justified since we already observe saturation of the pump transition in the superradiant laser and in view of rapid rotational relaxation. However, in practice, a large volume of gas could be used if necessary to reduce the pumping energy density.

The upper limit of 150 J/pulse can presently be reached with CO_2 transversely excited atmospheric pressure lasers or with lasers using electron beam pumping.

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REFERENCES

[1] D. L. Jassby, D. R. Cohn, B. Lax, and W. Halverson, "Tokamak diagnostics with the 496-micron CH_3F lasers," Princeton Plasma Phys. Lab., Princeton Univ., Princeton, N. J., Rep. MATT-1020, pp. 1–12, Jan. 1974; also, B. Lax and D. R. Cohn, "Interaction of intense

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submillimeter radiation with plasmas," in *Proc. Int. Conf. Submillimeter Waves and their Applications* (Atlanta, Ga.), June 1974.
[2] F. Brown, S. R. Horman, and A. Palevsky, "Characteristics of a 30-kW-peak 496 μm methyl fluoride laser," *Opt. Commun.*, vol. 9, pp. 28–30, Sept. 1973; also, T. A. DeTemple, T. K. Plant, and P. D. Coleman, "Intense superradiant emission at 496 μm from optically pumped methyl fluoride," *Appl. Phys. Lett.*, vol. 22, pp. 644–646, June 1973.
[3] F. Brown, S. Kronheim, and E. Silver, "Tunable far infrared methyl fluoride laser using transverse optical pumping," in *Proc. Int. Conf. Submillimeter Waves and their Applications* (Atlanta, Ga.), June 1974.
[4] P. V. Avizonis and R. L. Grotbeck, "Experimental and theoretical ruby laser amplifier dynamics," *J. Appl. Phys.*, vol. 37, pp. 687–693, Feb. 1966.
[5] J. F. Figueira *et al.*, "Nanosecond pulse amplifier dynamics," *Appl. Phys. Lett.*, vol. 22, pp. 216–218, Mar. 1973; also, G. T. Schappert, "Rotational relaxation effects in short-pulse CO_2 amplifiers," *Appl. Phys. Lett.*, vol. 23, pp. 319–321, Sept. 1973.
[6] T. Y. Chang and T. J. Bridges, "Laser action at 452, 496 and 541 μm in optically-pumped CH_3F," *Opt. Commun.*, vol. 1, pp. 423–426, Apr. 1970.

Optimal Design of Optics for Submillimeter Astronomy

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***Abstract*—We have designed two- and three-element shaped reflecting telescopes which minimize diffraction losses and sidelobes for submillimeter radiometric and spectrometric application. New solutions for the near-field output of an off-axis paraboloid when illuminated with a beam of considerable power taper (20 dB) show the merit of using Gaussian illumination for which the feed telescope may be explicitly designed. Conventional long-focus Cassegrain telescopes can, by using a suitably positioned off-axis conic to give a condensed focal patch, be converted for submillimeter sky chopping.**

I. INTRODUCTION

Major constraints in designing counterparts to conventional optical instruments for submillimeter work are that instrument apertures are not very large compared to wavelengths, as is the case in optical astronomy, but that technology does not readily permit the extensive use of feed horns and waveguides as in radioastronomy. Although heterodyne techniques are being extended into the range, most observers use broad-band detectors in the form of doped Ge crystal bolometers and photoconductive devices, ideally of disk shape for axial symmetry. Lens optics have the drawback that all materials having suitable refractive indexes are also strongly selectively absorbing.

There is thus the need to optimize conventional reflecting optical telescopes and auxiliary systems in order to deploy the focused radiation in the plane of the detector so that its size is minimized, thereby improving the signal to noise ratio, and the radiation sidelobes are suppressed, improving photometric performance. We have, in recent work [1], [2], proposed effective solutions for three types of observations: straightforward photometry with a Cassegrain-like telescope, amplitude- and phase-modulated Fourier spectrometry with Michelson interferometers. In this letter we also describe three-element telescopes designed for radiometry.

II. TWO-ELEMENT SYSTEMS

In reshaping the conventional Cassegrain telescope, we have found a microwave analog most useful. Pratt [3], [4] has shown how to derive a desired focal plane distribution (FPD) corresponding to a given angular beam pattern provided by a feed horn at the focus of a two-element telescope. We cannot use this method directly, since there is in any case no feed horn. Instead we solve the inverse problem of deriving the beam pattern from a given FPD, specified as that distribution which combined maximum possible axial concentration with minimum secondary diffraction maxima (sidelobes). The general expression for the FPD, $E(t)$ in terms of axial distance t, wavenumber $k = 2\pi/\lambda$ (wavelength λ), and angular beam distribution $f(\theta)$, i.e.,

$$E(t) = j(2\pi/\lambda)f_e E_0 \int_0^{\theta_0} f(\theta) \sin\theta \cos\theta J_0(kt \sin\theta)\, d\theta \quad (1)$$

where f_e is the focal length of the system, θ_0 the cutoff angle corresponding to the focal ratio, and J_0 refers to a zero-order Bessel function. It is fortunate that in this expression the two functions $E(t)$ and $f(\theta)$ form a Hankel transform pair, so that given $E(t)$ one can derive $f(\theta)$ either from the transform equation:

$$f(\theta) = k^2 \int_0^{\infty} E(t) J_0(kt \sin\theta)\, t\, dt \quad (2)$$

or for computing purposes, following Ruze [5] from its series approximation:

$$f(\theta) = \frac{2}{\sin^2\theta} \Sigma E\left(\frac{\beta_m/k \sin\theta_0}{J_0^2(\beta_m)}\right) J_0\left(\beta_m \left\{\frac{\sin\theta}{\sin\theta_0}\right\}\right) \quad (3)$$

with β_m the roots of the Bessel function and discrete ordinates t_m chosen from $\beta_m = kt_m \sin\theta_0$. After various trials it was found that the FPD most suitable for transformation was given by

$$E(t) = \exp\left[-\alpha(t/t_0)^2\right] \quad (4)$$

i.e., a Gaussian. On transformation this yields a Gaussian angular distribution

$$f(\theta) = \exp\left[-\gamma(\theta/\theta_0)^2\right] \quad (5)$$

but this would retransform to the original sidelobeless pattern only in the limit where $\theta_0 = \pi/2$, i.e., an $f/0$ focal ratio. For realistic θ_0 values, e.g., $\theta_0 = \pi/6$ (i.e., $f/0.9$) the retransformed FPD has sidelobes, but much suppressed compared with those of a conventional diffraction-limited aperture, or Cassegrain system of equivalent focal ratio, and the energy is more compactly distributed in the focal plane.

Having designed the beam shape, the mirror shapes are then derived from ray traces plus the power conservation theorem, somewhat after Galindo [6] and Williams [7]. This is a fairly conventional procedure, but the ability to set input power equal to zero over that part of the incoming wavefront behind the secondary reflector enables power blockage to be minimized, and the efficiency thus to be optimized. Fig. 1 shows the profile of a Cassegrain-like

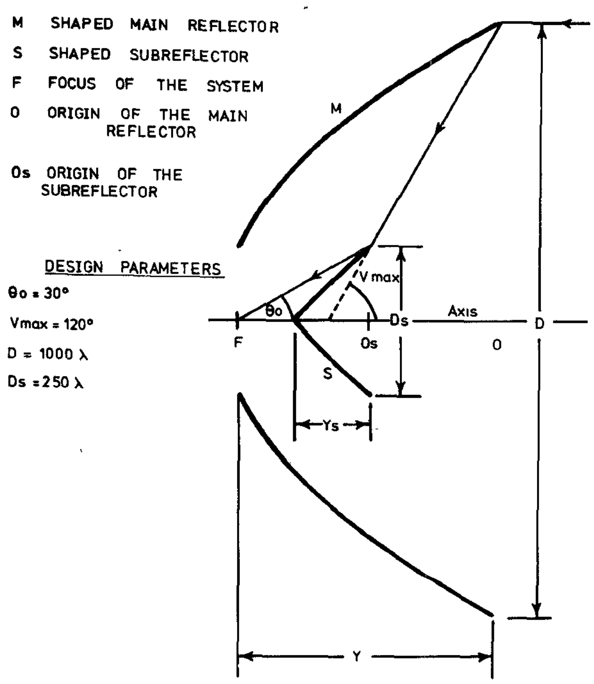

Fig. 1. Cross section of shaped two-element submillimeter reflecting telescope.

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