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GUIDING OF VERY INTENSE LIGHT PULSES FOR LASER ACCELERATORS

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(Presented to the "Workshop on Laser Acceleration of Particles", Los Alamos, February 18-23, 1982)

ABSTRACT

The field distributions and physical properties of several waveguides capable of transporting near infrared laser pulses are reviewed, with the aim of assessing the maximum transportable power and the limit fields in the laser beam.

INTRODUCTION

One of the main problems encountered in the conceptual design of laser accelerators is the periodic refocusing of light pulses having a peak fluence density of the order of some Tw/cm^2. In fact, in the so-called far-field acceleration schemes the electron is subject to the combined action of a slow-wave (wiggler field or microwave field) and a powerful laser beam along a straight trajectory.

For a acceleration gradient of 1 GeV/m, and an energy of 1 TeV, the laser photon bunches have to be guided over a distance of 1 Km with good collimation. The coherent interaction with the slow-wave and the electron can be only achieved by containing the deformation of the light wavefronts within the limits of fractions of wavelengths. If these requirements are quite difficult to meet when the fluence density is small, in case of very energetic pulses the damage to dielectrics and metals establishes a sharp threshold for the power density of the fields to be kept confined.

The fact that dielectrics and metals can withstand fluence densities which do not exceed the value of 10^{-3}-10^{-1} Tw/cm^2, does not automatically exclude the possibility of achieving the required guiding action on the beam by resorting to hollow dielectric or metallic guides. A way to concile higher fluence densities with relatively low damage threshold is to accurately shape the beam so as to obtain a fluence along the bunch trajectory much higher than that in the vicinity of the guiding structure. A second factor which could help is connected with the grazing incidence of the beam. While current data on laser damage have been taken by normal incidence irradiation of the sample, we can speculate that the threshold should increase for grazing incidence in view of the drastic reduction of the field inside the dielectric.

In the present contribution we intend to examine the problem of propagation through dielectric and metallic waveguides. We will address the problem from both the electromagnetic point of view and the laser damage of dielectric and metallic materials.

DIELECTRIC WAVEGUIDES

Basically, the guiding properties of these structures are associated with the process of total reflection, according to which a light beam traveling in a medium possessing and index of refraction n_1, can be totally reflected when impinging on a discontinuity surface separating the first medium from a second one having a refractive index $n_2 < n_1$. The waveguides most widely used for propagation over long distances have cylindrical symmetry (see Fig. 1).

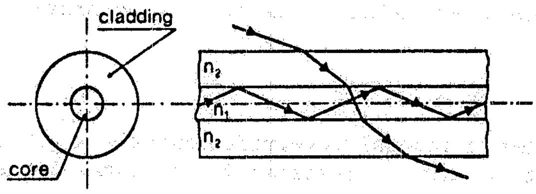


FIG. 1 - Cylindrical dielectric waveguide.

The propagation of electromagnetic waves in these structures can be analysed by considering the field as a superposition of modes, characterized by a space dependence of the form $\exp(-i\beta z)$, z being the axial coordinate.

From a physical stand-point the modes separate in two classes, guided modes and radiation modes according to whether the power carried along the propagation axis is conserved or not.

Solving Maxwell's equations, it can be shown(1) that the electric, E_z, and magnetic, H_z, axial components of a guided mode can be written as :

$$H_z(\varrho,\Phi) \propto E_z(\varrho,\Phi) \propto \begin{cases} J_\nu(x\varrho)\, e^{i\nu\Phi}, & \varrho \leq a \\ \dfrac{J_\nu(xa)}{K_\nu(\gamma a)} K_\nu(\gamma\varrho)\, e^{i\nu\Phi}, & \varrho > a \end{cases} \tag{1}$$

Here x and γ are related to the longitudinal propagation constant β through the relations :

$$\omega^2 \mu_o n_1 = \beta^2 + x^2 , \qquad \omega^2 \mu_o n_2 = \beta^2 - \gamma^2 \tag{2}$$

ν is an integer index, a is the radius of the inner region of the guide and K_ν is the modified Bessel function of order ν. The other components of the e.m. field can be obtained from

Maxwell's equations. When the relative difference between the inner and outer refractive indices is much less than unity, a set of linearly polarized modes $(LP)_{\nu\delta}$ can propagate. The transverse electric components of these modes read:

$$(E_x)_{\nu\delta} \propto \binom{\sin \nu\Phi}{-\cos \nu\Phi} \times \begin{cases} \dfrac{J_\nu(x\varrho)}{J_\nu(xa)}, & \varrho \leq a \\ \dfrac{K_\nu(\gamma\varrho)}{K_\nu(\gamma a)}, & \varrho > a \end{cases} \tag{3}$$

A similar equation holds for $(E_y)_{\nu\delta}$.

The constants β, x and γ depends on ν and δ through the characteristic equation:

$$\frac{J_\nu(xa)}{xaJ_{\nu+1}(xa)} = \frac{K_\nu(a)}{\gamma a K_{\nu+1}(\gamma a)} . \tag{4}$$

For $\nu = 0$, the fields of the dielectric cylinder break into TM $(H_z = 0)$ and TE $(E_z = 0)$ modes just as in the case of the metallic cylinder. For $\nu \neq 0$, hybrid modes, designated NE_m and EH_m, exist for which both E_z and H_z are non-zero. The designation HE and EH is given depending on whether or the largest contribution to the transverse field comes from H_z or from E_z.

An important mode parameter is the cutoff frequency, that is the frequency below which the mode becomes radiative. The cutoff conditions for the various mode types can be shown to be:

$$\left.\begin{matrix} EH_{\nu\delta} \\ EH_{1\delta} \end{matrix}\right\} J_\nu(xa) = 0 ,$$

$$HE_{\nu\delta} \quad (n_1^2 + 1) J_{\nu-1}(xa) = \frac{xa}{\nu - 1} J\ (xa), \qquad \nu = 2, 3, \ldots\ldots \tag{5}$$

$$\left.\begin{matrix} TE_{o\delta} \\ TM_{o\delta} \end{matrix}\right\} J_o(xa) = 0 .$$

Note that the cutoff frequency of mode HE is zero. For frequency much larger than the cutoff frequency the characteristic equation simplifies notably into:

$$xa\, J_{\nu+1}(xa) = V J_\nu(xa) \tag{6}$$

where V is the so-called <u>normalized frequency</u> defined as:

$$V = a(x^2 + \gamma^2)^{1/2} = ak(n_1^2 - n_2^2)^{1/2} . \tag{7}$$

By simple algebra it can be shown that eq. (4) yields:

$$xa = (xa)_\infty \left[1 - \frac{2\nu}{V}\right]^{1/2} \tag{8}$$

for $\nu \neq 0$, and

$$xa = (xa)_{\infty} e^{-1/V} \tag{9}$$

for $\nu = 0$, $(xa)_{\infty}$ being the zero of the equation $J_{\nu}(xa) = 0$.

A plot of the normalized propagation constant β/K for a few of the low order modes is shown in Fig. 2.

For operating the waveguide single-mode, V must be chosen less than 2.405.

As V increases, each mode becomes more strongly confined to the core and the fraction of power in the cladding approaches zero[(2)]. Far from cut off, Marcuse has obtained an asymptotic expression for P_{clad}/P.

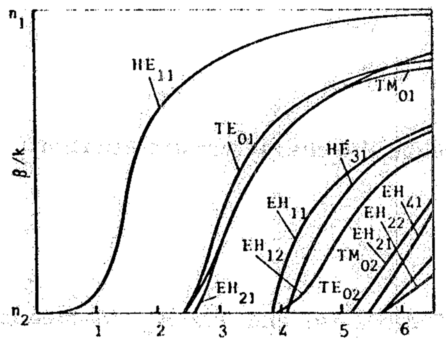


FIG. 2 - Propagation constant normalized frequency.

$$\frac{P_{clad}}{P} = \left[(xa)_{\infty}\right]^4 \frac{1}{V^4} \left(1 - \frac{2}{V}\right). \tag{10}$$

For the HE_{11} mode at V = 2.405, 84 % of the power travels within the core. At V = 10, the fraction of power reduces to 2.58 ‰.

It is also important to notice that for V = 2.4, xa = 1.68. Consequently, the field on the interface core-cladding is equal to:

$$\frac{E(a)}{E(o)} = J_o(1.68) \sim 0.4\,. \tag{11}$$

Far from cutoff we have for the HE_{11} mode:

$$\frac{E(a)}{E(o)} = J_o\left[2.4\, e^{-1/V}\right] \underset{V \to 0}{\longrightarrow} 0\,. \tag{12}$$

Consequently, for reducing the field strength in the cladding it is necessary to use higher values of V. This requirement contrasts with the circumstance that small irregularities of the interface can scatter mode HE_{11} into the higher modes with cutoff frequencies less than V. However, there is no physical reason why this phenomenon should notably influence the propagation of a light pulse over a distance of a few hundred meters. While in optical fibers used for telecommunication, the geometrical irregularities occur on a scale of a few microns and are conditioned by the physical process of pulling the fiber from molten glass, for guiding the beam of a laser accelerators it would be necessary to use a hollow dielectric fiber with an inner diameter of a few millimeters.

The optical quality of the inner surface could be controlled mechanically to obtain a good optical finish.

Various types of middle-infrared optical fibers have been developed through intensive efforts to realize low-loss optical transmission of higher-power CO_2 laser beams. Sakuragi et al.[3] have recently developed a polycrystalline KRS-5 (thallium-bromide-iodide) optical fiber having a high-power transmission capability for cw CO_2 laser beams. A sample of fibers obtained by extrusion, 1 mm in diameter was found to remains free from damage up to a power flux of 30 KW/cm^2. Bridges et al.[4] have been able to grow fibers made with single-crystal AgBr. These infrared crystalline fibers have potentially extremely low losses. By reducing the metallic impurities by 4 orders of magnitude an attenuation of $\sim 10^{-3}$ dB/Km at 5 μm should be obtained. These fibers have the potential for high infrared power transmission.

Hidake et al.[5, 6] have also proposed a new type of middle-infrared optical fiber in which oxide glass is used as the cladding material to define a hollow core. When the refractive index of the cladding material is smaller than unity, then there exists a critical angle for rays impinging on the core-dielectric interface from the hollow-core side. As already reported by Cleek[7], some materials have strong absorptions in the middle infrared region (800-1200 cm^{-1}) due to lattice vibrations. Consequently, on the high frequency side of the absorption land the real part of the refractive index is notably less than on the lower frequency side. For some materials, e. g. SiO_2, the reduction is so strong as to give a value of $n_r < 1$. Hidake et al. have remeasured accurately the reflectivity of fused silica, Pb glass and SF-6 glass and have found frequency intervals in the spectral region covered by CO_2 lasers, in which the refractive index is less than unity. They have also tested a hollow-core Pb glass fiber having an inner diameter of 1 mm. A loss factor of 7.7 dB/m was measured. It is worth noting that these losses compare well with those obtainable with a metallic silver waveguide having the same diameter. By making n_r small enough, the field remains confined within the core region and the oxide-glass-cladding will not be damaged.

HOLLOW DIELECTRIC WAVEGUIDES SUPPORTING RADIATIVE MODES

Hollow dielectric waveguides were first suggested by Marcatili and Schmellzer[8] as guiding media for gaseous lasers. Laser action in dielectric waveguides filled with He-Ne and CO_2 has been demonstrated by Smith[9], Bridges et al.[10], Burkhardt et al.[11], Jenson et al.[12], Degnan et al.[12], Chester et al.[14], Marcuse[15] and Laakmann et al.[16]. Different materials like BeO and Al_2O_3 in form of capillary tubes with bore diameters ranging between 1 and a few millimeters have been also used.

More recently several groups have built rectangular structures because of the ease of obtaining polished internal walls. The rectangular structures are fabricated from four polished slabs of dielectrics fitted together to form a hollow rectangular structure. By using slabs with corrugated surface these waveguides can be transformed into distributed feedback lasers in which the stationary wave pattern is obtained by coupling the two counterrining waves through the periodic wall corrugations.

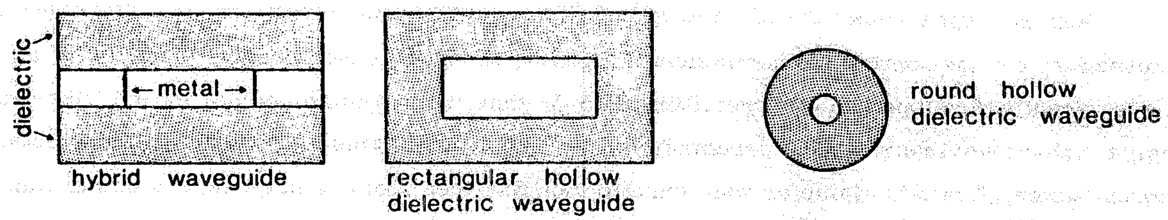


FIG. 3 - Hollow dielectric waveguides.

Hollow dielectric waveguides do not support guided waves in the usual sense. In conventional dielectric waveguides guidance is achieved by total internal reflection. In hollow-core waveguides the "cladding" has a refractive index which is larger than that of the core ($n=1$). This means that the critical angle is complex. Consequently, we can expect that the propagation constant β of the "radiative" modes supported by these structures is intrinsically complex, i. e. independent of possible losses in the dielectric. Marcuse(15) has calculated the loss coefficient of these leaky modes in parallel plates hollow dielectric waveguides. For TE_{oi} modes he has obtained:

$$\alpha_i^{TE} = \frac{(1+1)^2 \pi^2}{2(n^2-1)^{1/2} K^2 a^3} \tag{13}$$

while for the TM_{oi} modes it can be shown that:

$$\alpha_i^{TM} = \alpha_i^{TE} n^2 . \tag{14}$$

More accurate calculations for rectangular waveguides have been carried out by Laakmann and Steier.

By limiting ourselves to the parallel plates case we have that the transverse distribution of the electric field of a TE_{oi} mode is of the form:

$$E(x) \propto \cos \varkappa x \tag{15}$$

where the generally complex transverse propagation constant K is related to the longitudinal propagation constant $K_z = \beta + i\alpha$ through the equation:

$$\varkappa^2 + \beta^2 - \alpha^2 + 2 i \alpha\beta = K^2 . \tag{16}$$

As a first approximation we can put:

$$\varkappa = \frac{\pi}{2a} - i\chi_i \tag{17}$$

where

$$\varkappa_i \sim \alpha_{01}^{TE} \varkappa \frac{2a}{\pi} = \frac{4\pi}{(n^2-1)^{1/2}} \frac{1}{Ka^2} \tag{18}$$

Consequently, the ratio between the field on the walls and on the center reads :

$$\frac{E_{wall}}{E_{center}} = \sinh(Ka^2 \frac{2}{\pi} \alpha_{01}^{TE}) \sim \frac{2}{\pi} Ka\ a\ \alpha_{01}^{TE} \sim \frac{4\pi}{(n^2-1)^{1/2}} \frac{1}{Ka} \qquad (19)$$

with a spacing of > 1 mm, we can easily obtain a reduction of the field on the wall of 10^{-2}.

Equation (18) also shows that as a rule this reduction is proportional to the factor $a\alpha^{TE}$. Consequently, we can affirm that as a general rule a reduction of the transmission losses positively affects the effective field strength in the dielectric.

METALLIC WAVEGUIDES

A number of metallic waveguides have been studied in the search for flexible systems able to deliver the output of CO_2 lasers. All these devices, the best understood being rectangular, helical and circular guides, share the feature of efficiently transmitting low-order modes.

The waveguide studied by the Center for Laser Studies, U.S.R. (see E. Garmine et al. Refs. 17-20) consists of two metallic strips separated by slimstocks whose sides form the sidewalls (see Fig. 4). It allows the propagation of TE and TM modes.

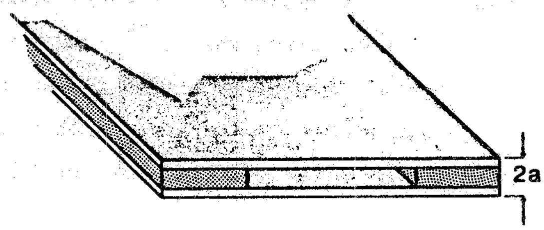


FIG. 4 - Metallic waveguide consisting of two metallic strips separated by slimstocks whose edges form the sidewalls.

Customarily the waveguide height 2a is much smaller than the widths so that the propagation is insensitive to the presence of sidewalls and occurs as through two parallel infinite plates. The modes are given by:

$$\underline{E} \propto \hat{y} \sin\left[\frac{m\pi}{2a}(x-a)\right] \exp(-i\beta_m z) \qquad TE_{mo} \text{ mode}$$

$$\underline{E} \propto \hat{x} \cos\left[\frac{m\pi}{2a}(x-a)\right] \exp(-i\beta_m z) \qquad TM_{mo} \text{ mode} \qquad (20)$$

with $\beta_m = \left[K^2 - (m\pi/2a)^2\right]^{1/2}$.

These waveguides exhibit strong attenuation. The relative loss factors can be calculated by a simple ray-optical analysis. In fact, a mode TE_{mo} or TM_{mo} is formed by two plane waves travelling at angle $\vartheta_m = \lambda_m \pi/2a$ with respect to the waveguide axis. Then, each ray travels a distance $d_m = a/\tan\vartheta_m$ between two reflections on upper and lower plates. Let $A(\vartheta)$ the loss per reflection at the incidence angle $i = \pi/2 - \vartheta_m$, the mode undergoes an attenuation per unit length equal to:

$$\alpha_m = \frac{m\lambda A(\vartheta)}{2a^2} . \qquad (21)$$

A being the absorptance of the metal at the grazing angle ϑ.

For grazing incidence $A(\vartheta)$ is given by (see f. i. Ref. 17):

$$A^{TE}(\vartheta) = 4\,\mathrm{Re}(n^{-1})\sin\vartheta \cong 4\vartheta\,\mathrm{Re}(n^{-1}) ,$$
$$A^{TM}(\vartheta) = \frac{4\,\mathrm{Re}(n)\sin\vartheta}{1 + 2\,\mathrm{Re}(n)\sin\vartheta + |n^2|\sin\vartheta} \tag{22}$$

n being the generally complex refractive index of the metal. Consequently,

$$\alpha_m^{TE} \sim \frac{m^2\lambda^2}{a^3}\,\mathrm{Re}(n^{-1}) , \qquad \alpha_m^{TM} \sim \frac{m^2\lambda^2}{a^3}\,\mathrm{Re}(n) . \tag{23}$$

A transmission of more than 95 % per meter in a straight alluminum waveguide having a cross section of 0.5 x 7 mm has been measured at $\lambda = 10\ \mu$.

It is noteworthly that α^{TE} scales with the inverse cubic power of the waveguide height. Consequently, using a waveguide 5 mm high the attenuation reduces to $5 \times 10^{-5}\ m^{-1}$.

Another factor to be considered is the ratio between the electric fields on the walls and in the middle of the waveguide for the TE_{10} mode, which exhibits the lowest losses,

$$\frac{E_{wall}}{E_{center}} = \frac{1}{2}|A| = \frac{1}{2}\,4\,\mathrm{Re}(n^{-1})\,\frac{\pi\lambda}{2a} = \frac{\pi\lambda}{a}\,\mathrm{Re}(n^{-1}) . \tag{24}$$

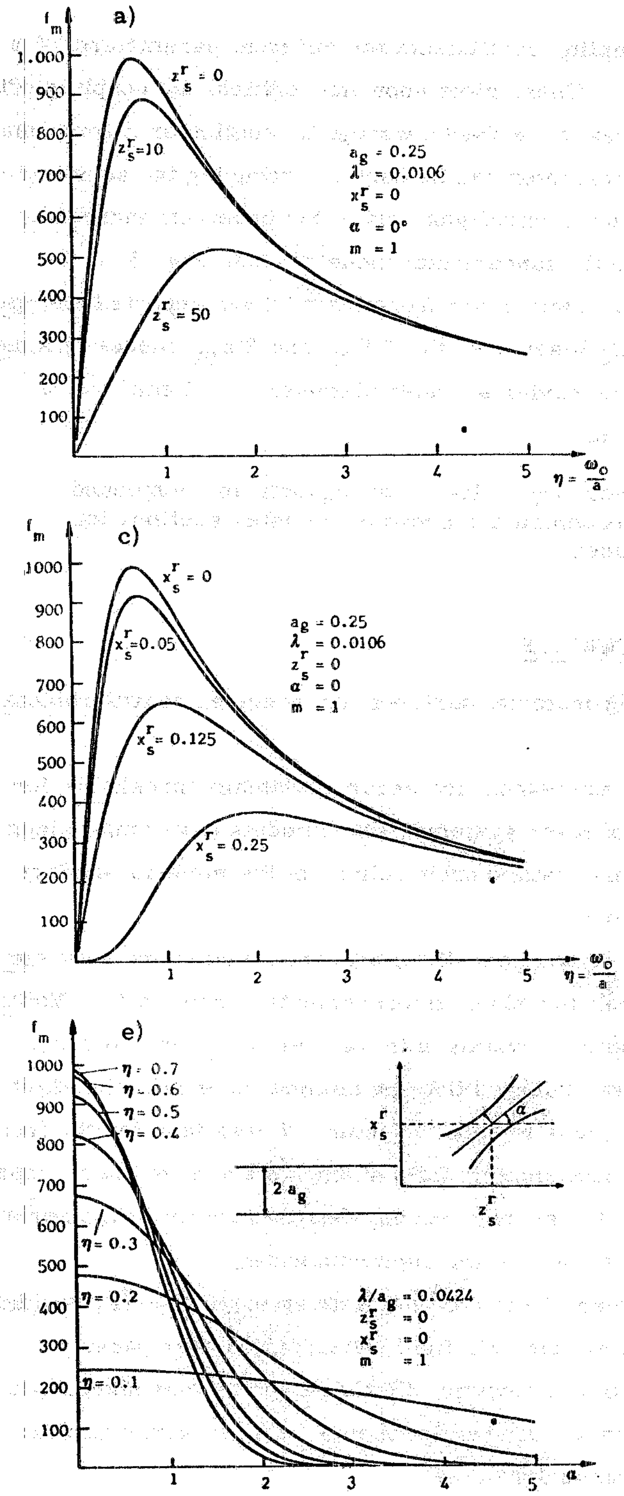
Since n oscillates between 60 and 70 for Al, Cu or Au, the above ratio is of the order of:

$$\frac{E_{wall}}{E_{center}} \sim \frac{0.5 \times 10^{-3}}{a} \tag{25}$$

with "a" expressed in mm. With a spacing of a few millimeters the field on the walls reduces to 10^{-3}- 10^{-4} of the value in the middle. This reduction is of the same order of magnitude of the reduction which can be reasonably achieved in a hollow dielectric waveguide.

If we assume that E_{center} can reach values of the order of a few GV/m, a rough estimate of the field inside the metal yields E_{metal} MV/m. This field corresponds to a flux density of $\sim 10^5\ W/cm^2$. The same intensity can be reached by illuminating the metal almost at normal incidence with a flux density of $\sim 10\ MW/cm^2$, having assumed a reflectivity of 99 - 98 %. Good quality copper mirrors can withstand such high flux densities for a few nanoseconds.

If we illuminate a metallic waveguide with a well focused beam, we can excite a few modes in such a way as to keep the field on the walls below the damage threshold value. This means that the most critical stage of this system concerns the coupling of the input beam with the waveguide. In case of Gaussian beam, the percentage of power channeled through any waveguide mode can be calculated by assimilating the beam to that irradiated by a source located at a complex point. In so doing it is possible to apply the geometrical theory of diffraction (GTD) which can account very accurately for the geometry of the metal[(21)]. In Figs. 5 a, b, c, d, e, f, g we have



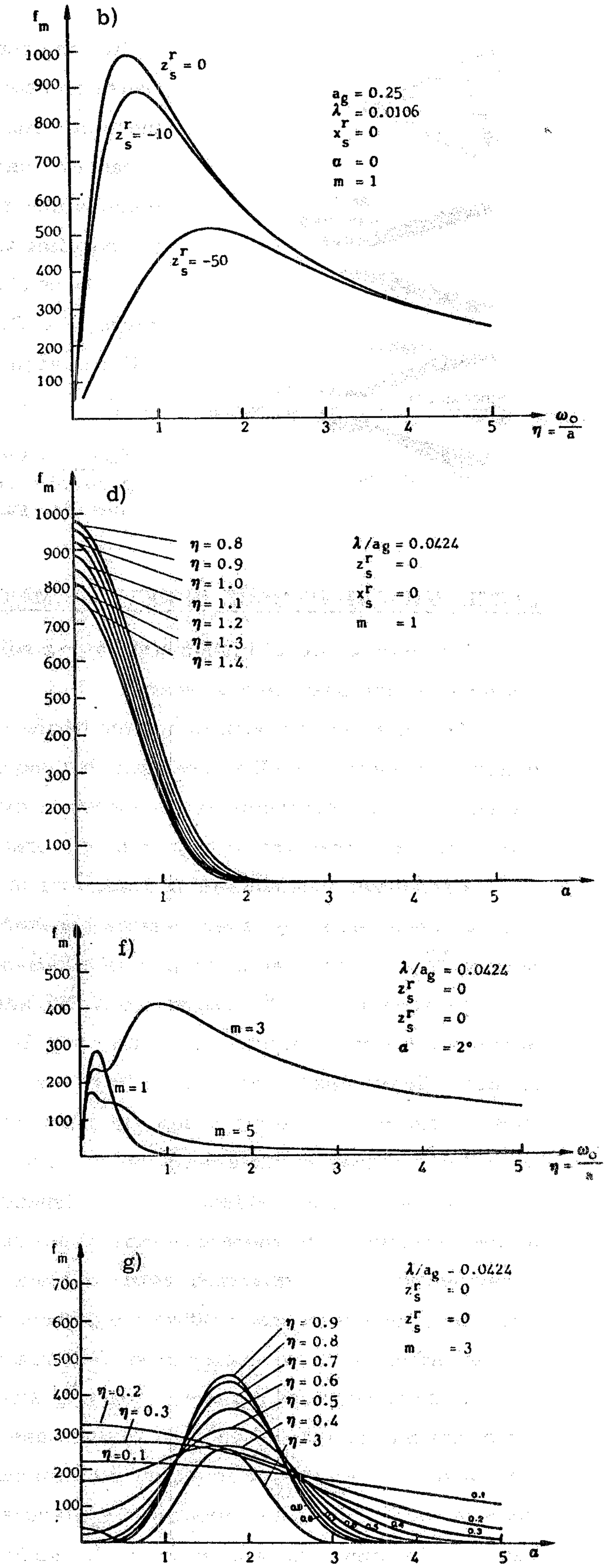
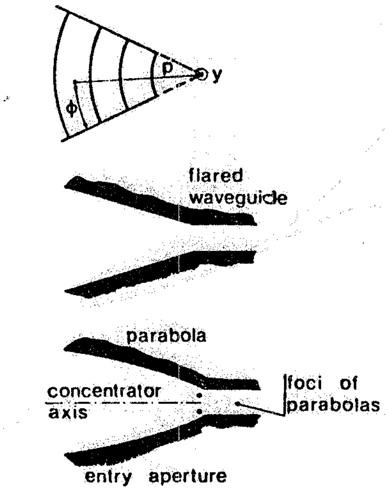


FIG. 5 - Coupling coefficient of a Gaussian beam with the fundamental (m = 1) and third (m = 3) modes of a metallic waveguide as a function of $\eta = \omega_o/a$, α and the coordinates x^r_s, z^r_s of the waist, α the angle formed by the propagation axis of the beam with the waveguide.



plotted the coupling coefficients for different parameters of a Gaussian beam. These plots show how critical the coupling with these structures is. A flared waveguide section or a compound parabolic concentrator can be used for reducing the sensitive of these guides to the misalignments of the beam and increasing the coupling to the fundamental mode(21) (see Fig. 6).

Recently, Marhic and Garmire(21) have reported the operation of a CO_2 laser over the TE_{01} and TE_{02} modes of a metallic waveguide having an inner diameter of 1.1 mm and a length of 3.4 cm.

FIG. 6 - Geometry of flared waveguides and compound parabolic concentrators proposed as input sections for metallic guides.

LASER INDUCED DAMAGE IN OPTICAL MATERIALS

The interaction of high-power lasers with material surfaces has received considerable attention over the past several years.

The interest has been motivated by the requirement for accurate damage thresholds for optical components to allow realistic designs of laser systems. Experiments have emphasized the laser power requirements necessary to cause catastrophic failure of the material surface due to melting, fracture or slip plane distorsions.

Breakdown mechanisms in insulators at dc and near-IR optical frequencies are very similar, as documented by laser-induced breakdown threshold measurements carried out by Yablonovitch(22) who irradiated samples of alkali-halide crystals with 10.6 μm CO_2 laser pulses.

Crisp et al.(24, 25) (see also Ref. 26) have observed that the nominal external intensity for damage at the rear surface of a plane parallel glass is about a factor 1.5 less than for the front surface. These results seem to indicate that local electric field strengths are of primary importance in determining surface damage either on the average energy density present at the surface or on the direction of the electric vector with respect to the surface normal.

Another indirect evidence of this dependence from electric field strength only is provided by the lowering of the damage threshold due to the electric field enhancement near pares, scratches and incipient cracks on the surface of a dielectric. Bloembergen(27) has shown that this reduction can be quantitatively explained by accounting for the correct depolarization factor depending on the geometry of surface cracks and grooves.

If these considerations are correct, we should observe an increase of the damage threshold at grazing incidence. In fact, in this case the reflectivity is almost equal to unity and the field inside the dielectric is a very small percentage of the incident one. However, we cannot disregard the role of the surface irregularities, for which there is no field reduction. In any case careful measurements of these threshold under grazing incidence and different surface finishing would produce a wealth of basic data.

The large number of experimental data relative to alcali-halides shows no variation attributable to frequency change alone, of the absolute magnitude of the breakdown threshold at 10.6, 1.06 and 0.694 μm. Thus, up to ω of almost 3×10^{15} Hz the basic behaviour of bulk dielectric breakdown is quite similar to the dc behaviour. This is attributable to the fast hot electron collision process and to the large material bandgap as compared to the photon energy.

For shorter wavelengths multiphoton absorption processes become most relevant and produce a lowering of the damage threshold.

Since the breakdown process depends on thermal diffusion (particularly for long-duration pulses) or to plasma growth by electron diffusion from an initial location, we can expect a square-root functional form ($\sqrt{Dt}$) of the time-dependence of the breakdown evolution. This leads to predict that the breakdown threshold electric field will scale like $t^{-1/4}$.

Damage of metallic mirrors strongly depends on the increase with temperature of the absorptance A. This parameter can be approximated by the relation

$$A = A_o + A_1 T_s \qquad (26)$$

T_s being the surface temperature. For damage at 100 ns in vacuum of clean-surface Portens et al.(28) have shown that the catastrophic failure of the material surface is due to melting.

A first principle calculation of the damage threshold based on the above equation and on the melting criterion for these materials by Sparks et al.(29, 30), has given a value close to 45 J/cm^2 for Cu at 10.6 μm and 100 ns.

More complex phenomena characterize the damage induced by pulses lasting a few nanoseconds. Observations of the morphology of laser induced damage in copper mirrors irradiated with a succession of 1.7 ns CO_2 laser pulses, have been reported recently by Thomas et al.(31). In particular they have observed that initial damage occurs at isolated sites due to random surface imperfections as for transparent dielectrics. After repeated irradiation the entire surface appears covered by an array of spheres with a rather uniform diameter of 1 μm. These alterations of the surface structure of polished copper mirrors take place at a fluence level a factor 4 below that required for single-shot surface damage (11.2 J/cm^2).

While for transparent dielectrics the damage threshold depends on the strength of the electric field inside the material, the factors controlling the damage of metals seems to be the absorbed power. Consequently, a reduction of absorptance obtained by grazing incidence of the laser beam should produce a rather notable increase of the damage threshold. Accurate tests of metallic mirrors at grazing incidence would prove quite essential in assessing the order of allowed power leadings for different pulse lengths.

CONCLUDING REMARKS

The reader is justified in questioning how well founded is the suggestion of using dielectric or metallic waveguides for confining and guiding the very powerfull laser beams required by laser accelerators, over distances of some hundred meters. Inquiry of the laser damage literature to date indicates that wide-bandgap insulators can withstand rms optical electric fields ranging from 1 MV/cm to 10 MV/cm depending on the pulse duration. These field breakdown thresholds correspond to flux densities of $\sim 10^{-3} - 10^{-1}$ Tw/cm^2.

The experimental data refer to the case of normal incidence. In case of grazing incidence we can expect a notable increase of the damage threshold. If we assume that the damage originates in the bulk of the dielectric the above quoted values of electric field will modify as

$$\frac{E_{normal}}{E_{grazing}} = \left(\frac{T_{graz}}{T_{nor}}\right)^{1/2} \qquad (27)$$

where $T_{nor} = 4n(n+1)^2$ is the transmission coefficient for normal incidence while T_{graz} refers to the case of grazing incidence at angle $\vartheta (\ll 1)$.

From Fresull's equations on reflectivity for optical quality surfaces we have at near incidence

$$T^{TE} = \frac{4\vartheta}{n} , \qquad T^{TM} = 4\vartheta n . \qquad (28)$$

So that we have

$$\begin{aligned} E_{threshold} &\sim \vartheta^{-1/2}(1-10)\ \mathrm{MV/cm} \quad (TE) \\ &\sim \frac{\vartheta^{-1/2}}{n+1}(1-10)\ \mathrm{MV/cm} \quad (TM) . \end{aligned} \qquad (29)$$

If we assume that our dielectric waveguide is used to confine a gaussian beam having a spot-size ω_o, we obtain a rough estimate of the incidence angle in the above relation by equating ϑ to the far field aperture, i. e.

$$\vartheta \sim \frac{\pi\lambda}{\omega_o} \qquad (30)$$

ω_o being the waist spot-size. So that,

$$E_{threshold} \sim \left(\frac{\omega_o}{\pi\lambda}\right)^{1/2}(1-10)\ \mathrm{MV/cm} . \qquad (31)$$

If we consider that the field on the wall is equal to that on the axis times $\exp(-a^2/w^2)$, we obtain a rough estimate of the highest rms field obtainable in the center of a hollow dielectric waveguide

$$E_{max} \sim \left(\frac{\omega_o}{\pi\lambda}\right)^{1/2} e^{a^2/\omega_o^2} / (1-10)\ \mathrm{MV/cm} . \qquad (32)$$

As an example, if we choose $a = 1.5$ mm, $\omega_o = 1$ mm, $\lambda = 10.6$ μm, we obtain

$$E_{max} \sim 8 - 80 \text{ GV/m}. \quad (33)$$

These values are of the correct order of magnitude compared to laser fields considered for acceleration where useful gradients of 0.1 - 1 GeV/m, are assumed.

ACKNOWLEDGEMENTS

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