WAVEGUIDE PROPERTIES OF A TUBULAR LIGHT BEAM

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The waveguide properties of a tubular light beam are investigated. The beam alters the properties of the medium so that the beam's trail becomes a waveguide for the passage of other radiation. Two types of variation of the medium properties, due to heating and ionization, are considered and the time of formation and lifetime of such a waveguide are evaluated. It is shown that such a waveguide can be used for the propagation of longer wavelengths: microwaves, infrared, and sound waves. It is noted that the waveguides can arise spontaneously in the presence of troughs in the laser intensity distribution.

1. INTRODUCTION

LASER sources of intense low-divergence light beams have recently become available. The energy and power of these beams are so high that they can alter the properties of the medium through which they propagate. For example heating of the medium reduces its density, ionization decreases the index of refraction of the medium, etc. These changes can occur either some time after the beam was turned on (for example the onset of thermal expansion is determined by the propagation time of sound waves through the affected volume) or during the existence of the beam (such as ionization), while the lifetime of these changes can vary in response to various factors. For example the heating dissipation time $t \sim l^2/\kappa_T$, where κ_T is the thermal conductivity of the medium (neglecting convection), can many times exceed the energy input duration.

Sharp changes in the properties of the medium exposed to laser beams and the low divergence of these beams can be used to achieve a waveguide propagation of longer wavelengths such as radio emission, ultrasound, long-wavelength light, etc. The use of the ionization column in a long spark as guiding and antenna systems for radio emission was suggested in[1,2]. Ionizing ultraviolet rays as radiowave transmission lines were later discussed by Rivlin (private communication). The waveguide propagation of an ultrasonic beam along the thermal trail of a light beam in a dense medium was investigated in[3].

In the present paper a tubular light beam is considered as a waveguide for the propagation of other wavelengths. The special tubular cross section of the light beam provides a waveguide capability for the internal transmission of radiation flux in the many cases of practical interest in which the solid beam trial discussed above is not feasible or effective as a waveguide.

2. FOCUSING CONDITIONS

The alteration of medium properties can result in two processes that eliminate the divergence of the transmitted radiation: refraction towards the interior and edge reflection.

Since the "glancing angle" varies as $d\theta/dz \approx dn/d\rho$, the refractive concentration of beam energy requires that the index of refraction n decrease away from the axis, i.e., that $dn/d\rho < 0$ while the velocity of propagation increases in the direction away from the waveguide axis. A drop of $\Delta n \approx \theta^2$ is necessary to maintain a beam with constant divergence θ. For the case of diffraction divergence, $\theta_d \approx \lambda/a$ where λ is the wavelength and a is the waveguide radius, and therefore $\Delta n \approx \theta_d^2 \approx (\lambda/a)^2$.

Since both heating and ionization in gases and in some dense media decrease the refractive index of the medium, a tubular beam may be suitable as the waveguide. The beam represents the "walls" of the waveguide and has the required sign of the gradient $dn/d\rho < 0$ at the internal surface to achieve internal focusing of the radiation (this requirement cannot be met in a solid beam forming the waveguide).

In addition to the refractive containment another containment regime is possible utilizing large coefficients of reflection from the transition layer, in which the medium properties change, at small angles of incidence: if $\theta \ll \sqrt{|\Delta n|}$, the coefficient of reflection from a sharp property discontinuity is $R = 1 - 4\theta/\sqrt{|\Delta n|} \rightarrow 1$ and the containment of radiation in the waveguide can occur with any sign of Δn. The sharpness criterion of the discontinuity (the applicability of Fresnel equations to a sharp boundary) at small angles of incidence is $\lambda\!\!\!^{-}/\theta > \delta$, where δ is the thickness of the transition layer in which the index of refraction undergoes change (in the case of refractive divergence this is always true when $\delta < a/2\pi$). Since a small portion of the energy of the contained radiation escapes via the refracted rays the Q of such a waveguide is lower than that of the refractive waveguide (the length of waveguide damping due to refraction is $L \approx a/\theta\ (1 - R) \approx a\sqrt{|\Delta n|}/4\theta^2 \approx a^3\sqrt{|\Delta n|}/4\lambda^2$). The possibility of using a refractive-index jump of any sign in edge reflection focusing extends the opportunities for achieving waveguide propagation, even though this method does require large amplitudes of variation of the refractive index.

3. PROPAGATION OF RADIO AND LIGHT RADIATION ALONG THE TRAIL OF A TUBULAR LIGHT BEAM

We first consider the variation of the index of refraction due to heating. If this variation is caused only by density changes in heating then

$$\Delta n_T \approx \frac{dn}{d\rho}\frac{d\rho}{dT}\Delta T \approx \frac{dn}{d\rho}\rho\frac{\Delta T}{T} \approx (n-1)\frac{\Delta T}{T}$$

for the case of gaslike media (when $n - 1 = A\rho \ll 1$). This change in density is created in time $t_s \gtrsim l/c_s$, where l is the characteristic dimension of the heated volume and c_s is the velocity of sound. Consequently the beam forming the waveguide does not respond to this change in the refraction index and is not defocused if the beam lifetime $t < t_s$. Usually $t_s \approx 10^{-5} l \approx 10^{-4}$–$10^{-3}$ sec for $l \approx 10$–100 cm, while the beam lifetime can vary from several nanoseconds to fractions of a millisecond.

For waveguide propagation of infrared radiation w with a wavelength of $\lambda = 10\ \mu$ given a waveguide radius of $a \approx 10$ cm it is sufficient that $\Delta n \approx (\lambda/a)^2 \approx 10^{-8} \approx 10^{-3} p_{atm} \Delta T/T$; this is readily accomplished with moderate heating at $\Delta T \approx 3 \times 10^{-3}$ deg. The required energy expenditure for heating a unit volume of gas is $W \approx N_L p_{atm} k \Delta T \approx 10^3 \Delta n N_L kT \approx 10^{-6}$ J/cm^3, where N_L is the Loschmidt number and k is the Boltzman constant; under these conditions ~10 J of energy must be expended on a waveguide 1 km in length.

Waveguide propagation of radio emission with a wavelength of $\lambda = 3$ cm, given a thermal waveguide radius of $a \approx 10^2$ cm generated by a ring system of lasers, requires that $\Delta n \approx (\lambda/a)^2 \approx 10^{-3}$. This case requires a very strong heating of the medium, $\Delta T \sim T$, which is obviously undesirable. In this case however we can ionize the medium by the light flare of avalanche ionization, multiphoton ionization of the host atoms of the medium, photoionization of readily ionized impurities, or ionization with an ultraviolet beam. (The last mechanism was examined in detail by L. A. Rivlin—private communication).

If the variation in the refractive index is due to ionization then $\Delta n_p \approx \omega_p^2/2(\omega^2 + \nu_s^2)$ where ω_p is plasma frequency ($\omega_p^2 = 4\pi e^2 N_e/m$) and ν_s is the electron-atom collision frequency ($\nu_s = N_A \sigma_s \nu_e$, where $N_A \approx N_L p_{atm}$, $\sigma_s \approx 10^{-15}$ cm^2, and $v_e \approx 10^7$–10^8 cm/sec, depending on the electron temperature. For $p = 1$ atm and $v_e = 3 \times 10^7$ cm/sec we obtain $\nu_s = 10^{12}$ sec^{-1}). Ionization causes a drop of $\Delta n \approx 10^{-3}$ at $\omega_p^2 \approx 2 \times 10^{-3}(\omega^2 + \nu_s^2) \approx 2 \times 10^{-3}\nu_s^2 \approx 2 \times 10^{21}$ sec^{-2} (when $\omega < \nu_s$); this corresponds to plasma concentration of $N_e \approx 10^{12}$ cm^{-3}. Such a plasma can be obtained for example by photoionization of readily ionized impurities (such as alkali impurities) that are always present in the air (a concentration of $\sim 3 \times 10^{-6}$% is sufficient). Although the lifetime of free electrons in the atmosphere amounts to fractions of a microsecond before capture the plasma trail can last longer because the electrons can be heated or re-excited by the microwave radiation itself that is contained by the tubular plasma waveguide. In such a case the light beam merely traces or initiates the waveguide. The intense light field can also cause decay of the negative ions and prevent electron capture. This process can occur with adequate probability, owing to the low energy of the capture bond.

The energy expenditure on the formation of this plasma is $W \approx N_e I$, it is of the order of 10 μJ per cm^3 (the energy expended on the formation of a free electron depends on the mechanism of formation, varying from the ionization potential (in photoionization) to a value that is several times larger in the presence of losses on the excitation of atoms and molecules during the avalanche development). The total energy input necessary to create the waveguide amounts to several hundred Joules.

The distance L along which the cylindrical shape of the waveguide is preserved depends on the divergence angle of the radiation forming the waveguide: $L_1 \approx 0.1a/\theta \sim 10^{-2}a$ for a real multimode divergence at $\theta \approx 10^{-3}$ rad and $L_d \approx 0.1a^2/\lambda$ for a diffraction divergence (we assume for the sake of simplicity that the thickness of the waveguide walls is commensurate with the radius of the waveguide). If the wavelength of the radiation forming the waveguide is $\lambda \approx 1\ \mu$ and $a \approx 10^2$ we obtain for the two cases $L_1 \approx 100$ m and $L_d \approx 10^5$ m respectively.

Tubular light and microwave beams can also be used[4] for the transport of plasma, charged particles, and atoms.

4. PROPAGATION OF SOUND ALONG THE TRAIL OF A TUBULAR LIGHT BEAM

We now consider the formation of waveguides for acoustic radiation. If the velocity of sound in the medium decreases on heating ($dc_s/dT < 0$ which takes place in many dense media) the thermal trail of a solid light beam can serve as a sound guide (we discussed this case in[3]).

However there are media in which the velocity of sound increases upon heating. For example in all gases $c_s \sim \sqrt{T}$ and $dc_s/dT \approx c_s/2T \approx 10^2$ cm/sec · deg. Therefore tubular light beams should be used for the formation of sound waveguide.

To compensate for the divergence θ_s of the sound beam it is necessary that $\theta \lesssim \sqrt{\Delta c_s/c_s} \approx \sqrt{\Delta T/2T} \approx \sqrt{10^{-3}\Delta T}$.

For example to compensate for diffraction divergence $\theta_d \sim \lambda/a \sim 0.1$ a heating of $\Delta T \sim 10$ deg is sufficient for refractive containment. Edge reflection also can be effective due to the presence of a density jump.

Focusing and waveguide propagation of sound, ultrasound, and hypersound by light beams characterized by intensity troughs can occur not only by design but also spontaneously due to the inhomogeneous distribution of intensity in the laser beam.

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