EXTREMELY LOW-LOSS HOLLOW CORE WAVEGUIDE FOR VUV LIGHT

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Received 3 August 1982
Revised manuscript received 8 October 1982

A new type of an extremely low-loss optical waveguide is proposed. In the vacuum-ultra-violet (VUV) region (wavelength less than 300 nm) most solid-state materials have a refractive index less than unity due to plasma vibration of electrons. The energy of VUV light is confined within the hollow core due to the smaller n_r than unity of the cladding material of the hollow core waveguide. Typical expected loss for 50 nm-wavelength VUV light of a 0.1 mm hollow-core waveguide is on the order of 0.05 dB/km.

The progress in optical-fiber technology is one of the most interesting and important developments for the recent communication engineering. The best data of the loss of silicate glass optical fibers is 0.2 dB/km [1]. For extremely long range communication systems (up to 1000 km) the 0.2 dB/km loss is insufficient, resulting in many relay amplifier stations. Therefore, a new optical fiber with a loss less than 0.1 dB/km is well desirable for future communication systems. Infrared optical fibers are proposed with alkali halides [2] or fluorides [3] as core material. The losses of these infrared-transparent optical fibers are expected to be less than 0.01 dB/km.

In this letter, a new type of extremely low-loss optical waveguide is proposed.

Recently, we proposed [4] a mid-infrared transparent hollow-core optical waveguide with oxide-glass cladding. The principle is as follows: When, at the frequency used, the refractive index n_r of the cladding (wall) material is less than unity, then we can construct a low-loss hollow core optical waveguide, because the light wave is confined within the hollow-core region due to the total reflection of the light incident from the core region to the cladding surface. The oblique incident light to the cladding material with n_r less than unity must be reflected mostly.

There are two energy regions showing n_r less than unity in solid-state materials. One is the mid-infrared (near to 1000 cm^{-1}) region due to lattice or molecular vibrations of ionic materials [4]. The other is the vacuum ultra-violet (VUV)-light region for almost all materials (including metals and dielectrics). For a frequency higher than the material's plasma frequency ω_p, which definition will be given hereafter, the material has a dielectric constant $\epsilon = \epsilon' - i\epsilon''$ with [5]

$$\epsilon' = 1 - (\omega_p/\omega)^2,$$

$$\epsilon'' = (\omega_p/\omega)^3(1/\omega_p\tau),$$

$$(\omega \gtrsim 2\omega_p), \quad (1)$$

where $\omega_p = (4\pi Ne^2/m^*)^{1/2}$ is the plasma frequency of the material with electron density N and effective mass m^*. τ in eq. (1) is the electron's mean free time. Typical value of ω_p is about 10^{16} s^{-1} (= 200 nm in wavelength), and that of τ is 10^{-14} s. Thus, for λ = 100 nm VUV light, $\epsilon' = 0.75$ and $\epsilon'' \approx 10^{-3}$ or $n_r \approx \sqrt{\epsilon'} = 0.866$ and $K = \epsilon''/2n_r = 0.58 \times 10^{-3}$ from eq. (1). n_r (real part of the complex refractive index $n_r - iK$) is enough smaller than unity to construct hollow-core waveguides. At the same time, the loss term ϵ'' or K is very small so that we have a strong possibility to get an extremely low-loss hollow-core optical waveguide. Fig. 1 shows $\epsilon = \epsilon' - i\epsilon''$

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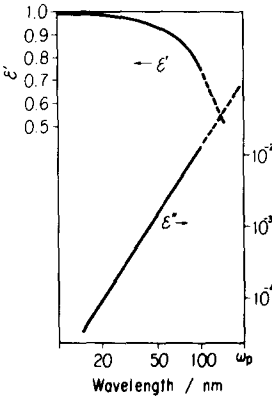

Fig. 1. Dielectric constant $\epsilon' - i\epsilon''$ of a material with plasma frequency ω_p = 200 nm.

versus wavelength λ (nm). The loss term ϵ'' reduces to ω^{-3}. Now we roughly estimate the transmission loss of the VUV hollow-core waveguide of which the structure is shown in fig. 2. We assume the waveguide is constructed by two plane cladding plates; the separation is a_0. This model corresponds to the so called meridional-ray approximation for cylindrical step-index optical fibers. The lowest-loss mode for such waveguides is TE_{01} mode, in which the electric field is parallel to the surface of the two walls. The reflection coefficient $\Gamma_{Te_{01}}$ of the TE wave is given as

$$\Gamma_{TE_{01}} = \frac{\cos\theta - (\epsilon_1 - \sin^2\theta)^{1/2}}{\cos\theta + (\epsilon_1 - \sin^2\theta)^{1/2}}, \tag{2}$$

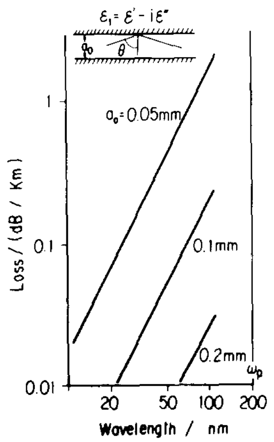

Fig. 2. Model and loss of a hollow-core optical waveguide. ω_p is assumed 200 nm. The lowest-loss mode is TE_{01}.

where θ is the incident angle shown in fig. 2. For the TE lowest-loss mode,

$$\cos\theta = k_x/k_0 = \lambda/2a_0 \tag{3}$$

is deduced under the assumption that the field strengtl at the cladding boundary is nearly zero. This assumption is valid for $\Delta n = n_o - n_r > 0.1$, where $n_o = 1.0$ is the refractive index of core (air). In eq. (3), we assume $\lambda \ll a_0$ (typically λ = 100 nm and a_0 = 0.1 mm; $\lambda/a_0 = 10^{-3}$) resulting in $\sin^2\theta \approx 1$. Then,

$$\Gamma_{TE_{01}} = \frac{\lambda/2a_0 - (\epsilon_1 - 1)^{1/2}}{\lambda/2a_0 + (\epsilon_1 - 1)^{1/2}}. \tag{3'}$$

Moreover, using $\epsilon' \gg \epsilon''$, $\lambda/2a_0$ and careful but straightforward calculations, we get for the power reflection coefficient $R_{TE_{01}} = |\Gamma_{TE_{01}}^-|^2$;

$$R_{TE_{01}} \approx 1 - (\lambda/a_0)\epsilon''/(1-\epsilon')^{3/2}. \tag{4}$$

From eq. (1), $1 - \epsilon' = (\omega_p/\omega)^2$, and

$$R_{TE_{01}} = 1 - (\lambda/a_0)(1/\omega_p\tau). \tag{4'}$$

The reflection number n_θ per length L is given by

$$n_\theta = L/l_\theta = L/a_0 \tan\theta = \lambda L/2a_0^2, \tag{5}$$

where $l_\theta = a_0 \tan\theta$ is the skip distance between two faced walls. Finally, the transmittance $T_{TE_{01}}$ of the hollow core waveguide with the length L is

$$\begin{aligned} T_{TE_{01}} &= (R_{TE_{01}})^{n_\theta} \\ &= [1 - (\lambda/a_0)(1/\omega_p\tau)]^{\lambda L/2a_0^2} \\ &\approx 1 - (\lambda^2 L/2a_0^3)(1/\omega_p\tau), \end{aligned} \tag{6}$$

for small loss region $((\lambda/a_0)(1/\omega_p\tau) \ll 1)$. Results are shown in fig. 2 for three core sizes 0.05, 0.1 and 0.2 mm. The loss is extremely low. For example, a_0 = 0.1 mm hollow-core waveguide has a loss 0.1 dB/km at 70 nm. For the cladding material, we do not need any special materials because the fact that n_r or ϵ' is less than unity is due to the majority electrons in the material used. Any impurities are not the cause of transmission loss.

The excess loss may be originating from three causes. The first cause are the residual gas molecules in the hollow core. For VUV light expected to be used in our waveguide, gas molecules such as N_2, O_2, or H_2O show very strong absorption; we should vacuate the core region of the waveguide. Another method to reduce gas-molecule absorption is to fill the hollow waveguide with He-gas to exclude N_2 and so on. He gas shows an absorption peak wavelength of about 50 nm; the absorption must be weak for a wavelength longer than 50 nm.

The second cause of the excess loss is the excitation of the inner-shell electrons of the atoms constructing the wall of the waveguide. We should avoid the inner-shell-electron absorption wavelength.

The final and most important cause for the loss are the surface irregularities of the hollow-core waveguide. When two waveguide surfaces in fig. 2 have a large amount of irregularities, the propagating dominant (lowest loss) mode wave will be scattered into other lossy modes, or in the worst case, reflected into backward waves. We will discuss such irregularity loss briefly. The surface irregularities are described by a Fourier expansion of the core-size irregularity such as

$$a(z) = a_0 + \int_0^\infty A(\Omega) \sin(\Omega z + \phi)\,dz, \tag{7}$$

where $\Omega/2\pi$ is the inverse period of the Fourier expanded core-diameter irregularity. In eq. (7), a_0 is the average of the core diameter. The scattering of the dominant wave into other modes occurs under the phase matching condition

$$k_0 - k_s = \pm\Omega, \tag{8}$$

where k_0 is the wavenumber of the incident dominant wave and k_s is that of the scattered one. For back scattering, $k_s = -k_0$ giving $|\Omega| = 2k_0$ in eq. (8). Also for forward scattering, $k_s \approx k_0$ giving $|\Omega| \ll k_0$. Thus we treat the two cases separately. One is the $|\Omega| = 2k$ case (jagged roughness), and the other is the $|\Omega| \ll k$ (slow swell) case. First we treat the former case. For our purpose, the wavelength used is very short (less than 100 nm); therefore the irregularity period $2\pi/\Omega$ is also very short. In this case, the amplitude $A(\Omega)$ in eq. (7) is supposed to be very small. The reason is as follows: Our thin capillary hollow waveguide is fabricated by a rapid-pulling method from a melted thick glass pipe. The thick glass-pipe preform is firstly heated in a suitable furnace. The inner surface of the glass pipe is liquefied to get a strong surface tension for large Ω. Fig. 3 shows the relative

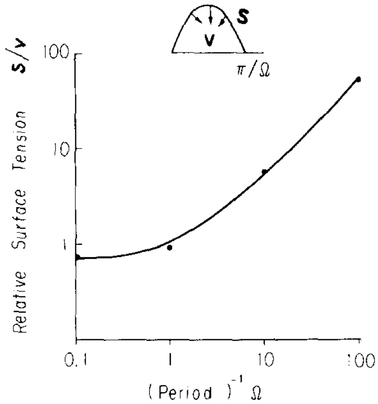

Fig. 3. Relative strength of surface tension s/v with period $2\pi/\Omega$.

strength of the surface tension s/v versus Ω, where v is the volume of the raised part modeled in fig. 3 as the irregularity (half part of $\sin \Omega z$);

$$v = \int_0^{\pi/\Omega} \sin \Omega z\, dz, \tag{9}$$

and s is the surface area of it,

$$s = \int_0^{\pi/\Omega} \left[1 + \left(\frac{d}{dz}\sin \Omega z\right)^2\right]^{1/2} dz, \tag{10}$$

here we treat only z-directional (wave propagation) irregularities. The surface-tension power is proportional to s given by eq. (10). As Ω increases, the relative surface tension s/v increases too, as shown in fig. 3. Thus we can assume the irregularity amplitude $A(\Omega)$ is

$$A(\Omega) \propto 1/\Omega. \tag{11}$$

Fig. 4 shows the experimentally measured surface roughness of the inner surface of a glass capillary by using TALY SURF surface meter. From this figure we can estimate that the roughness amplitude $A(\Omega)$ at $2\pi/\Omega = 10\ \mu$m is on the order of 0.05 μm; using eq. (11) we assume A at 210 nm to be less than 2 Å. Thus the jagged roughness with the same-order period to the dominant wave does not give any losses. This is an essential difference with polished surfaces.

For the case $|\Omega| \ll k$, namely long-wave swells, the irregularity corresponds to a change in the core diameter a. The dominant-mode transmission loss is in-

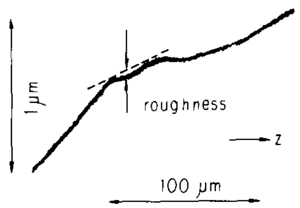

Fig. 4. Measured roughness of the inner surface of a glass capillary. Linewidth is due to the mechanical vibration, not due to real surface roughness.

versely proportional to a^3; we will calculate the average of a^3 of it, including the irregularities, and

$$\overline{a^3} = \int_0^\infty a^3 f(a)\,\mathrm{d}a$$

$$= \frac{1}{\sqrt{2\pi}\sigma} \int_0^\infty a^3 \exp\left(-\frac{(a-a_0)^2}{2\sigma^2}\right) \mathrm{d}a$$

$$= a_0^3 + 3a_0\sigma^2, \qquad (12)$$

where σ is the dispersion of the gaussian distribution $f(a)$ of the core-diameter irregularity and a_0 is the first order average of it. The long-range swells with a gaussian distribution correspond to an expansion of th core diameter resulting the loss reduction from eq. (6).

In conclusion, surface irregularities are not the mair cause of excess transmission loss.

References

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In dielectric materials, if the light energy is much higher than the material's band gap, the valence electrons will behave nearly as free electrons in metals.