Beam shape analysis of waveguide delivered infrared lasers

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Abstract. A comprehensive theoretical model is developed to describe mid-IR laser radiation propagation in an optical cylindrical waveguide. The effects of various parameters of the beam as well as of the waveguide on the output beam shape are studied and analyzed. Parameters such as beam coupling misalignment, waveguide diameters, and inner wall roughness are studied. The same conditions are applied in the theoretical calculations as well as in the experiments. Good agreement between the theoretical and experimental results is found. © 2002 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1420191]

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1 Introduction

One of the methods used to transmit mid-infrared (MIR) radiation from a source (laser, heat, or other IR source) to a target (tissue, detector), straight or under bent trajectory, is a hollow optical waveguide. Such waveguides were intensively studied and developed in the last decade. These types of waveguides are made of plastic or silica tubes and were already used for several applications in medicine. The practical applications revealed several drawbacks, which limited the extension of utilization into broader fields, such as noninvasive surgery, hard tissue cutting, or other procedures needing high power lasers. This was mainly due to the fact that the Teflon waveguides have large attenuation (A > 1 dB/m) and the silica waveguides are not flexible enough (bending radius bigger than 75 mm) for internal diameters of cross section (ID > 0.5 mm). This has led to studies of the radiation propagation through the bore of the guide (the role of the roughness of the internal wall of tube) and to the improvement of the deposited guiding layers (metal and dielectric), which may give lower attenuation. The analysis of the beam propagation until now was not accurate enough, since several parameters, which may affect the beam shape and divergence of delivered radiation, were not taken into account. These parameters are: the coupling of the IR source to the input, and roughness of the internal wall of the waveguide. Our theoretical model was refined to give quantitative representation of the relation between the beam profile and these indicated parameters. The results of calculations based on this model may contribute to the understanding of the laser radiation delivery in hollow optical waveguides in general, and ours in particular. The results of such a study will lead to the development of waveguides more suitable for a host of new applications in the fields mentioned before.

2 Experimental Procedure

The plastic and silica waveguides were prepared using the flow chemistry electroless method. Before the deposition of the guiding (Ag and AgI) layers, the internal wall of the plastic (Teflon) tube was etched with naphthalene/THF solution, followed by a second etching of sulfonic acid. After etching the wall, the tube was sensitized and activated by SnCl2/HCl and PdCl2/HCl solutions. For silver layer deposition, we used AgNO3 solution buffered by ammonia and acetic acid and a hydrazine hydrate solution as a reducer. The AgI layer was obtained by reacting the deposited silver with iodine solution. A similar method was applied in the preparation of the silica waveguides.

The attenuation of CO2 laser radiation (wavelength λ = 10.6 μm) transmitted by Teflon and fused silica waveguides (length L = 1.0 m and ID = 1.0 and 0.7 mm) was measured. The measurements were done using a Sinrad CO2 laser with maximum power of 15 W. Cutback and nondestructive methods were used for attenuation measurements. Beam shape measurements were done with the Spiricon beam shape analyzer, which was placed 10 cm after the waveguide’s end. Coupling of the laser beam to the waveguide was done with a ZnSe lens (f = 50 mm). The beam spot size at the waveguide input was 0.3 mm. The position of the laser beam at the center of the waveguide’s input was determined using a coaligned HeNe visible laser.

3 Effect of Surface Roughness

The procedure described in the previous section has two goals: the first is to deposit the thin films, which guides the laser beam through the hollow waveguide, and the second is to create a smooth and homogenous surface before deposing the thin layers. This is done by filling the cracks and voids beforehand in the hollow tube.

The surface roughness was measured using an atomic force microscope (AFM). Figure 1(a) shows the surface texture of the AgI layer. Analysis of the scan shows that the surface roughness (σ) is between 200 and 450 Å for glass waveguides and 937 Å for Teflon waveguides.

The distribution of heights was calculated by the AFM software and was found to be normally distributed [Fig.
The distribution of heights is given by

\[ w(z) = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(\frac{-(z-z_0)^2}{2\sigma^2}\right) \]  

(1)

where \( z_0 \) is the mean surface height.

The scattering coefficient for such a surface is given by Beckman\(^7\)

\[ \langle \rho \rho^* \rangle = e^{-\left[\frac{(\sin \varphi_1 L)^2}{\nu_1 L} + \frac{\sqrt{\pi} T^2}{2L} \right]} \times \sum_{m=0}^{\infty} \frac{g^m}{m! \sqrt{m}} \exp\left(-\nu^2_1 T^2/4m\right). \]

(2)

where \( \varphi_1 \) is the angle of incidence, \( \varphi_2 \) is the scattering angle, \( L \) is the length of the scattering surface, \( T \) is the correlation distance of the surface roughness (\( T \ll L \)) and

\[ \nu_1 = k (\sin \varphi_1 - \sin \varphi_2), \]

(3)

\[ F(\varphi_1, \varphi_2) = \sec \varphi_1 \frac{1 + \cos(\varphi_1 + \varphi_2)}{\cos \varphi_1 + \cos \varphi_2}. \]

(4)

\[ \sqrt{g} = \frac{\sigma}{\lambda} (\cos \varphi_1 + \cos \varphi_2). \]

(5)

To find the scattering coefficient, we should compute the series in Eq. (2). The series is calculated numerically until the last term is less than 0.01%. The scattering coefficient was calculated using the MATLAB program (version 5.2).

Figure 2 shows the scattering coefficient for various surface roughnesses. We can see that as the surface roughness increases, the normalized scattering coefficient decreases. The scattering coefficient, \( S \), for each ray is the sum of the normalized scattering coefficients for the positive angles divided by the sum of the normalized scattering coefficient for all angles [Eq. (7)].

4 Theoretical Model

A new ray model was used for calculation of the propagation of radiation through the waveguide and for the delivered beam shape.

According to the ray model,\(^{18,19}\) one can decompose the laser beam into separate rays. This model may be used, since in our case \( \lambda \ll d \), where \( \lambda \) is the wavelength of the coupled beam and \( d \) is the inner diameter of the waveguide’s cross section. We assume that multiple incidences on the metal (e.g., silver) and dielectric (e.g., silver iodine) layers guide the rays by refraction and reflection. The dielectric layer has a normal distribution of heights [Eq. (1)], which causes scattering.

The propagation of the rays was calculated using the physical laws of geometrical optics. The following conditions were used:

1. The Fresnel law gives the reflection coefficient after the incidence with the thin layer.
2. The rays propagate only frontal and not rotational (there are no skew rays).
3. Two coordinates represent the laser beam cross section and the point the ray enters into the waveguide: \( r \) (with Gaussian distribution) and \( \theta \) (with uniform distribution) (Fig. 3), where \( 0 \leq r \leq R \) (\( R \) is the laser spot size) and \( 0 \leq \theta \leq 2\pi \). The angle \( \theta \) also determines the plane in which the ray propagates.
4. The angle of entrance, \( \varphi \), (Fig. 3) has Gaussian distribution. This angle determines the angle of propagation, \( \phi \), by \( \phi = 90 - \varphi \).

5. The rays have random polarization, TE or TM.

6. The total energy of the laser beam, \( I \), is the sum of the energy of all rays, and is given by

\[
I = \sum_i I_i(\sigma_r, \sigma_\varphi, r_i, \varphi_i),
\]

where \( \sigma_r \) and \( \sigma_\varphi \) are the standard deviation of the Gaussian beam size and angle, respectively.

The new ray model adds the following assumptions:

7. The surface of the dielectric layer is rough.

8. The roughness centers are distributed randomly.

9. The scattering is produced only on the surface of the incident layer and not in the bulk of it (not inside the AgI layer), since the AgI layer is more granular than the Ag layer, hence roughness is higher.

10. The scattered energy is taken only in the positive direction; scattered energy in the negative direction is assumed lost. The scattering coefficient \( S \) is given by

\[
S = \frac{\sum_{\varphi = 0}^{90} S(\varphi)}{\sum_{\varphi = -90}^{90} S(\varphi)},
\]

where \( S(\varphi) \) is given by Eq. (2).

11. The scattering of the ray changes the ray’s angle of propagation. The new angle is the average angle of the scattered energy.

12. The laser beam is decomposed to a minimum of 10^5 rays.

Using these assumptions, one can calculate the attenuation and the beam shape outside the waveguide as a function of the waveguide’s parameters (length and inner diameter), and the coupling conditions (focal length of the coupling lens and off-center movement of the ray).

When the laser beam hits the waveguide’s inner wall, it undergoes two processes: reflection from a thin layer and scattering. According to the previous assumptions, the energy of each ray after one incidence with the inner wall is

\[
I_i = I_{i0} R(\varphi) S(\varphi),
\]

where \( R(\varphi) \) is the reflection coefficient given by Fresnel and \( S(\varphi) \) is the scattering coefficient.

5 Results and Discussion

The first attenuation and beam shape experiments were made on silica straight waveguides with internal diameter \( ID = 0.7 \) mm and length \( L = 1.0 \) m. Gaussian beam shape was measured. Low attenuation (less than 0.4 dB/m) was achieved. The attenuation as a function of the waveguide length is shown in Fig. 4(a), the beam shape measurement...
is shown in Fig. 4(b), and calculated in Fig. 4(c). As can be seen from the graph, the theoretical results are in agreement with the theoretical ones.

To compare between the two beam shapes, let us define the parameter $\xi$ which is the ratio of the $M^2$ factor of the experimental beam shape to the $M^{20}$ of the calculated beam shape.

$$\xi_x = \frac{M_{x,\text{exp}}^2}{M_{x,\text{cal}}^2},$$

$$\xi_y = \frac{M_{y,\text{exp}}^2}{M_{y,\text{cal}}^2}. \quad (9)$$

A good correlation is achieved when $\xi$ is close to one.

This experimental beam shape is quite similar to that of the source (not shown, since it was a regular Gaussian shape beam) except for a second satellite propagation mode of small intensity. A theoretical calculation, for the same condition, was done. The scattering due to roughness of the deposited layers (average roughness $\sigma \leq 500$ Å) was very small. The results of the calculations are shown in Fig. 4(b).

The calculated beam shape is similar to the experimental one ($\xi_x = 1.09, \xi_y = 0.99$). A significant result is that similar to the experimental case, a small ring of higher modes of propagation is also seen in the theoretical results [Fig. 4(b)]. The cause for the higher modes is the focal length of the lens. The smaller the focal length, the larger the number of angles that are propagating in the waveguide. This gives rise to higher modes.

The same measurements and calculations were repeated for a ID = 1.0 mm and ID = 0.5 mm waveguide. The results are shown in Figs. 5(a), 5(b), 5(c), and 5(d). When we compare the beam shapes shown in Fig. 5 and Fig. 4, we notice that with the increase of the ID from 0.5 through 0.7 to 1.0 mm, the number of propagation modes, which is seen in the beam profile, has increased, although the fundamental part remains of Gaussian shape. This result is shown experimentally and theoretically. The increase in the diameter caused more emphasized presence of the higher modes, as shown in Figs. 5(a) and 5(b) in comparison with that of
Fig. 4. This is due to the coupling between higher modes to lower ones, which occurs when the waveguide’s diameter decreases.\textsuperscript{21} The attenuation,\textsuperscript{18,19} on the other hand, is decreased.

The correlation for ID = 1 mm between the experimental Fig. 5(a) and the theoretical Fig. 5(b) results is rather good, (\(\xi_x = 0.85, \xi_y = 0.77\)). The correlation for ID = 0.5 mm between the experimental Fig. 5(c) and theoretical Fig. 5(d) results is rather good, (\(\xi_x = 1.02, \xi_y = 0.96\)).

A further increase of the ID drastically spoils the beam shape (result not shown), where there are much more modes in the output beam. This drastic change of the radiation energy distribution in the propagated beam is bad for medical applications. When the higher modes intensity grows, then the energy at the peak is lower, thus we have a beam with hot spots. This beam shape has a lower effectiveness when using it for precise laser cutting of tissue. A larger diameter with energy spread over it will cause lower energy densities, which cause bigger thermal damage. The laser spot at the output of a waveguide should be kept as small as possible, considering reasonable attenuation.

One other factor, which contributes to the deviation of the beam shape from Gaussian, is the off-center coupling of waveguide. This may happen, since there is always a problem in coaligning a laser beam to a small ID waveguide, especially in a medical laser where there are always movements of the articulated arm and the waveguide while an operation is performed. For the understanding of beam waveguide aligning problem and its affect on beam shape, we carried out the measurements described in the next paragraph.

The laser was first focused at the center of the waveguide’s input. Using the positioners, we moved the beam from the center toward the edges in both directions. We have taken images of all the output beams at different center locations. At each location, we have also measured the output energy. Out of this series of images, we have chosen to show three off-center couplings at 150, 300, and 400 \(\mu\)m. For the same locations, we have also applied our ray tracing program. Figures 6, 7, and 8 show the results of the experiment [(a) in each figure] and theoretical results [(b) in each figure]. It is obviously seen that when the beam is further out from the center, the beam is spoiled, symmetry is gone, the main peak is reduced, and higher modes appear. We can also see that our model predicts well the experimental results. The loss of symmetry is due to the large attenuation of the lower modes, which now propagate near the waveguide’s wall. When the lower modes are highly attenuated, the higher modes are more emphasized.

These experiments were repeated with a Teflon waveguide with internal wall roughness of about 1000 \(\AA\) (as measured with an atomic force microscope). The results are
shown in Fig. 9. The theoretical results and the experimental ones are similar ($\xi_x=0.84$, $\xi_y=0.87$). The effect of scattering due to the wall roughness on the beam shape at the output of the waveguides is very well pronounced. When we compare Figs. 5(a) and 9(a), we can see the effect of the roughness, which is $\sigma<500$ Å in the silica waveguide and $\sigma<1000$ Å in the Teflon waveguide. Bigger roughness causes much more scattering, thus a much less ordered beam shape. This output beam contains many more hot spots and less pronounced center peak. The theoretical results in Figs. 5(b) and 9(b) confirm these results.

Experiments with the waveguide mentioned before were carried out at the Vanderbilt Free Electron Laser facility. The free electron laser wavelength was tuned to 6.45 μm. The two types of waveguides were coupled through a 100-mm lens and the beam shape reading was done with the Spiricon and pyroelectric camera. Figures 10(a) and 10(b) show the results for Teflon and fused silica waveguides, respectively.

The two waveguides are multimode waveguides. A large amount of modes develop and are transmitted in these waveguides. These modes, of course, cause beam shapes, which are far from the Gaussian input beam and have the beam structure of multisots. In the more rough waveguides, mode coupling processes are present (due to the roughness), and this causes the smeared structure of the output beam in the Teflon waveguide. The fused silica waveguide, on the other hand, has much less roughness but there is a development of modes in it, and together with a not-so-pure Gaussian, like in the case of the CO₂ laser, creates the hot spot multimode shape at its output.

6 Conclusions

The ray model described predicts phenomenon in the beam shape, for the simple cases shown, quite accurately. We have noticed that an increase in the internal diameter of the hollow waveguide decreases the attenuation but increases the deviation of beam shape from Gaussian. Off-center coupling of the Gaussian shape of the laser source decreases the height of the fundamental mode and causes generation of satellites due to the development of additional modes. Roughness of the internal wall of the waveguide produces higher losses and a noisier beam shape.

In our future plans, we will take into our model more parameters, such as bending, non-Gaussian beam shapes, variation in the angle of the launched beam, introduction of the wavelength to the calculations, and pulse and short pulse treatment (i.e., pulse broadening, micropulses). We will consider various shaped distal tips and eventually wet field interaction (the effect of liquid phase on beam shape).
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References


Biographies and photographs of the authors not available.

Fig. 10 Free electron laser radiation transmission: (a) Teflon waveguide and (b) fused silica waveguide.