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THE EFFECT OF SCATTERING ON THE TRANSMISSION OF INFRARED RADIATION THROUGH HOLLOW WAVEGUIDES

M. Ben-David, A. Inberg, I. Gannot, N. Croitoru

Department of Electrical Egineering, Physical Electronics, Faculty of Engineering,
Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel

One of the most efficient ways of delivering mid-infrared ($2.5\mu m<\lambda<20\mu m$) radiation from a source (laser beam, black body or biological tissue), to a detector, through straight or bent trajectories, is a hollow waveguide. The infrared radiation is guided through the bore of waveguide by multiple reflections and refraction from metal and dielectric thin films respectively. One of the factors that determine the transmission of the hollow waveguide, is the surface roughness, which causes scattering. To find how does the roughness affects the transmission of the waveguide, we measured the surface roughness using an atomic force microscope (AFM) and developed a new ray model, which predicts the transmission and the beam shape delivered by the waveguide.

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1. Introduction

One of the methods used for delivery of mid infrared (MIR) radiation from a source (laser or heated object) to a target (tissue, detector), in straight or under bent trajectories is a hollow waveguide (WG). Such waveguides were intensively developed and studied in the last decade [1-10]. These types of waveguides made of plastic or silica tubes were already used for several applications in medicine [9-13]. The practical applications revealed several drawbacks, which limited the extension of utilization in broader fields as, e.g.: non-invasive surgery, dentistry or high power cutting lasers. This was mainly due to the fact that the plastic waveguides have big attenuation (A>1dB/m) and the silica waveguides are not flexible enough (bending radius bigger than 75 mm), for internal diameters ID>0.5mm. This has lead to studies of the radiation propagation through the bore of the WG (the role of the roughness of the internal wall of tube) and of the improvement of the deposited guiding layers (metal and dielectric), which may result in lower attenuation [14]. The obtained data was not accurate enough, since several important parameters, which may affect the beam profile and divergence of delivered radiation, were not taken into account. These parameters are: the coupling of the IR source to the input, the radius of bending, length, WG diameter, roughness of the WG's internal wall and the focal length of the coupling lens. A theoretical model was developed in order to describe quantitatively the relation between the beam profile and the above-indicated parameters. The results of calculations based on this model may contribute to the understanding of the experimental data obtained and presented in this paper. These results take into account: absorption losses, internal diameter and roughness effects on the delivered beam profile.

2. Hollow waveguides preparation

The guiding mechanism hollow waveguides developed by Croitoru *et al.* [1-2] are based on the deposition of thin layers (metal and dielectric) on the inner wall of flexible tubes (teflon, fused silica, polyimide). The deposition is done using an electroless method. In our case the metal film is Ag and the dielectric film is AgI (Fig.1). These layers guide the radiation through the internal air bore of the waveguide by means of reflection and refraction.

The hollow waveguide is made in several stages. The first operation is the preparing of the tube substrate which is followed by electroless deposition and process of its smoothing. If a plastic tube is used as a substrate the first stage is a combination of heating and pulling, either separately or simultaneously, to smoothen the surface of the tube. If the tube is glass or quartz, the tube is cleaned with concentrated HNO_3.

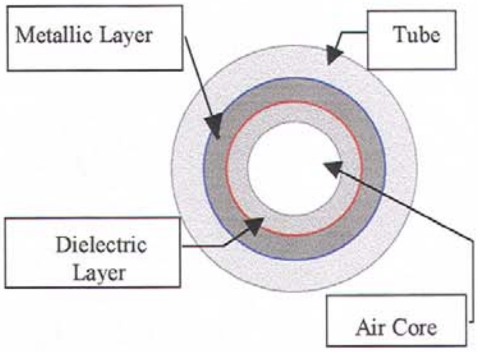


Fig. 1 Cross section of hollow waveguide.

The second stage is to fill the small voids, cracks and scratches in the tube to further smoothen its surface. This is done in an additive manner by filling the voids of the inner surface of the tube with coating materials (e.g. hydrophilic material having a free pair electrons and capable of complexing metal ions). Preferably, is to use as void filling material a polymer selected from the group of polymerized aliphatic amines and aromatic amines, such as polyaniline and amino silanes.

The next stage is the surface activation by depositing a palladium (Pd) layer or very small Pd particles. The thin film of Pd is a catalyzing layer for the electroless metal deposition.
Deposition of silver layer was made from $AgNO_3$ solution, buffered by ammonia and acetic acid. Hydrazine hydrate was used as a reducer, and deposition process was operated at room temperature. The metal layers could also serve as heat sink to dissipate heat, which is accumulate during the transmission of infrared radiation.

The completed stage is to treat the metal layer with a halogen to form a metal halide film. In our case I_2 in ethanol solution is used for producing AgI film.

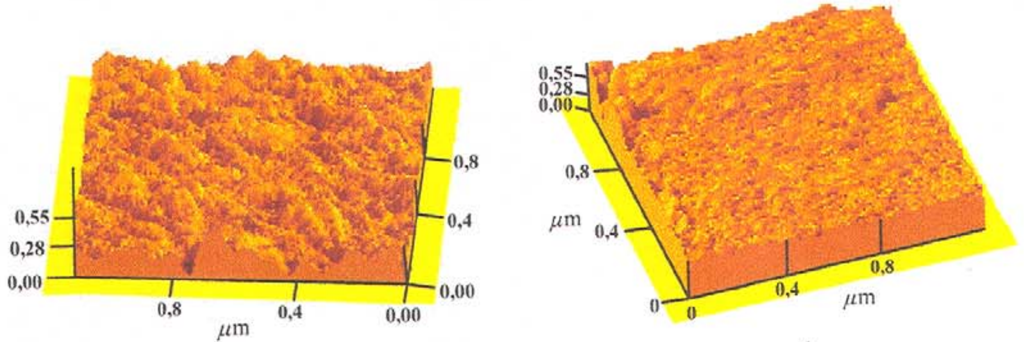
3. Surface roughness measurements

The procedures used during the process of deposition have two goals: a. To create smooth and homogenous surface b. To deposit the thin films, which will guide the radiation through the hollow waveguide. Special attention is concentrated to have very small roughness of the surface, which will give large transmission of the waveguide.

The surface roughness depends on the tube's internal wall on which the layers are deposited. The thickness of the dielectric layer (e.g. AgI) is calculated to avoid destructive interference at the wavelength the WG is optimized to.

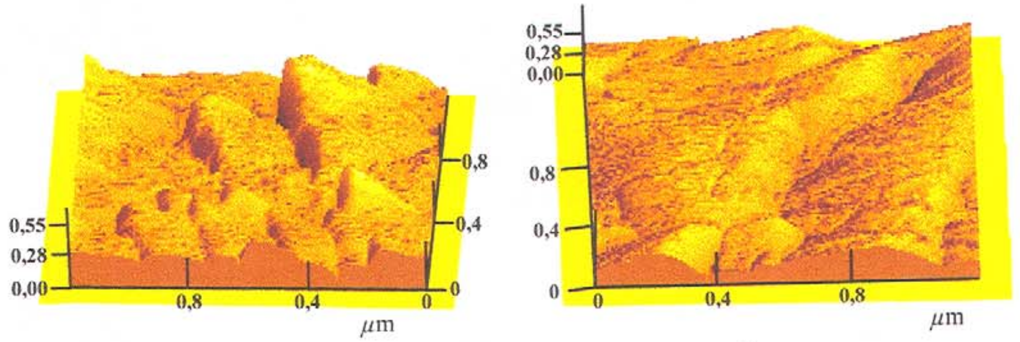
The surface roughness was measured using an atomic force microscope (AFM). In Fig. 2 is shown the surface morphology after each step of the process. As can be seen from Fig. 2 the roughness of the surface increases following the deposition process steps (from Fig. 2a to Fig. 2e) but still remains relatively small (roughness $\sigma \leq 24$ nm).

Similar measurements were made for waveguides prepared from teflon and polyimide tubes.



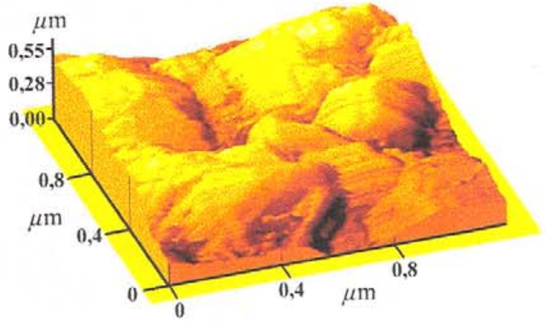
a
Fused silica tube
$\sigma = 0.4$ nm

b
Tube after applying silane
$\sigma = 5.5$ nm



c
Pd layer
$\sigma = 11$ nm

d
Ag layer
$\sigma = 10$ nm



e
AgI layer
$\sigma = 24$ nm

Fig. 2 Fused silica waveguide surface morphology after each step of the process.
(α is the surface roughness)

The high roughness of AgI layer on teflon WG (about 300 nm) and polyimide (about 100 nm) in comparison to the fused silica WG, is due to their higher own wall roughness before deposition of the guiding layers.

4. Ray model for infrared radiation transmission through hollow waveguide

One of the methods to describe the transmission of infrared radiation through hollow waveguides is the ray model. According to the ray model one can decompose the laser beam into separate rays. This model may be used since, in our case $\lambda << d$, where λ 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 of w *(z)*, given by:

$$w(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma^2}\right), \tag{1}$$

where z is the coordinate in the direction of propagation, which cause scattering.

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

I) The Fresnel law gives the reflection coefficient after the incidence with the thin layer.
II) The rays propagate only frontal and not rotational (there are no skew rays).
III) Two coordinates represent the laser beam cross section and the point the ray enters into the waveguide; r (with Gaussian distribution) and θ (with uniform distribution) (Fig. 3), where $0 \le r \le R$ (R is the laser spot size radius) and $0 \le \theta \le 2\pi$. The angle θ also determines the plane in which the ray propagates.

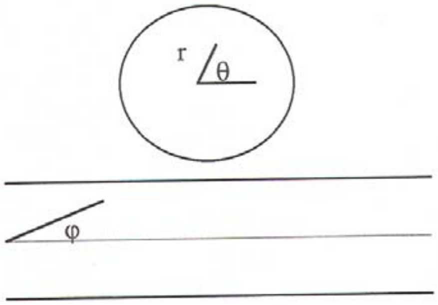


Fig. 3 The ray parameters.

IV) The angle of coupling φ, which is determined by the focal length, (Fig. 3), has Gaussian distribution. The angle of propagation, ϕ, is given by $\phi = 90-\varphi$.
V) The rays have random polarization, TE or TM.
VI) The total energy of the laser beam, *I*, is the sum of the energy of all rays, and is given by:

$$I = \sum_i I_i\left(\sigma_r, \sigma_\varphi, r_i, \varphi_i\right) \tag{2}$$

VII) The scattering is produced only on the surface of the incident layer and not in the bulk of it.
VIII) The scattered energy is taken only in the positive direction; scattered energy in the negative direction assumed lost.

IX) The scattering of the ray changes the ray's angle of propagation. The new angle is the average angle of the scattered energy.

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

Using these assumptions have calculated the transmission and the beam shape of the delivered waveguide as a function of the waveguide's parameters (length, inner diameter), and the coupling conditions (focal length of the coupling lens, off center propagation of the ray).

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

$$I_i = I_{i0} R(\varphi) S(\varphi), \tag{3}$$

where $R(\varphi)$ is the reflection coefficient given by Fresnel and $S(\varphi)$ is the scattering coefficient. The scattering coefficient is the scattered energy in the positive direction divided by the ray's energy. After the incidence with the wall we get a ray which propagates with a new angle φ, due to the scattering.

The waveguide's transmission is given by

$$T = \frac{I_{out}}{I_{in}} \tag{4}$$

Applying the ray model to WGs with different surface roughness shows that the high value of the ratio σ/λ (σ - the surface roughness and λ - the laser wavelength (10.6µm)), gives lower transmission. This is shown in Fig. 4.

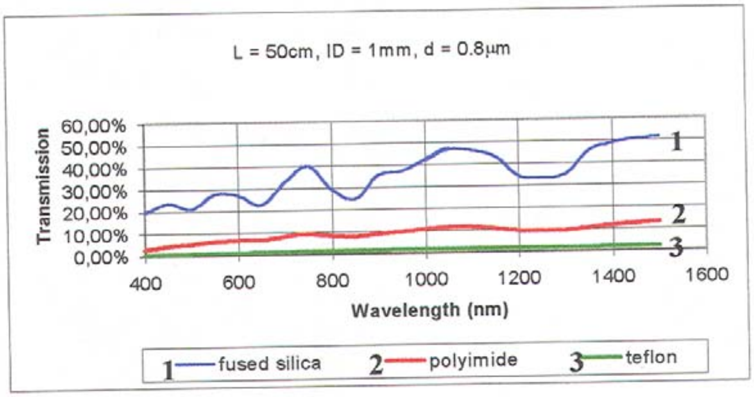


Fig. 4 Transmission as a function of wavelength (calculated).

The roughness of the inner wall of the WG also affects the beam shape of the laser delivered by it. Fig. 5 shows the calculated beam shape delivered by fused silica (a) and teflon (b) waveguides with inner diameter of 1 mm. As seen from Fig. 5 a and b, with increasing of surface roughness, higher modes of propagation appear.

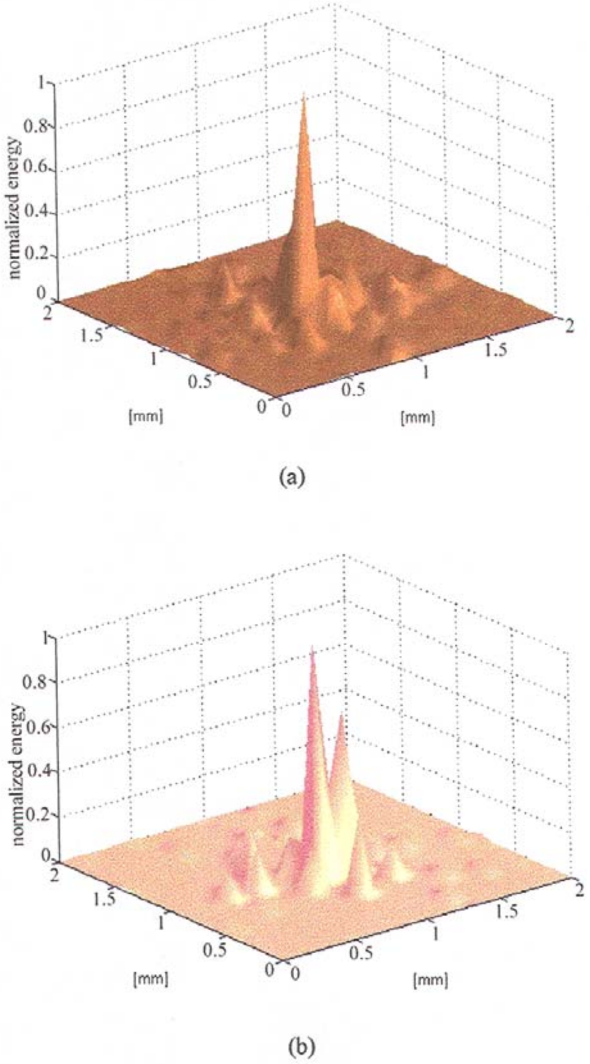


Fig. 5 Theoretically by calculated beam shape delivered by fused silica (a) and teflon (b) waveguides.

5. Experimental results

To see the influence of roughness we measured the transmission of three types of WGs (fused silica, polyimide and teflon) as a function of the wavelength. The experimental setup included monochromator, detector and hollow waveguides. The results are shown in Fig. 6. As seen in Fig. 6, transmission of fused silica (σ = 24 nm) is higher (for all values of λ), than that of polyimide (σ = 100 nm) and teflon (σ = 300 nm), waveguides, similar with the calculated results shown in Fig. 4. This is due to the difference in surface roughness of the waveguides as was mentioned above.

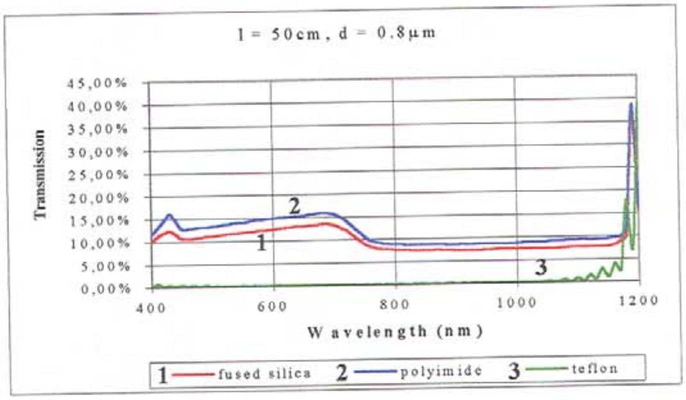


Fig. 6 Transmission as a function of wavelength (measured).

We checked the beam shape delivered by the WG using a beamshape analyzer. The results obtained for fused silica (a) and teflon (b) waveguides with inner diameter of 1 mm are shown in Fig. 7. The beam shape obtained experimentally is similar to those obtained for the theoretical ray model (Fig. 5).

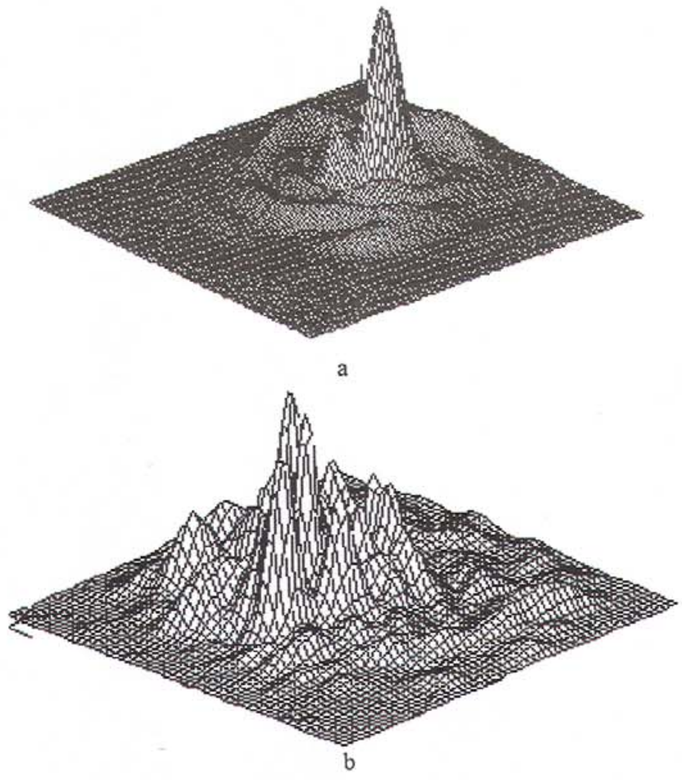


Fig. 7 Beam profile of fused silica (a) and teflon (b) waveguides ID = 1 mm.

6. Conclusions

The main contribution to the waveguide's roughness comes from the roughness of the substrate tube. The deposition of layers on the inner walls of the WG increases slightly the roughness of the WG surface. Using a ray model one can determine the transmission of the waveguide at different wavelengths for different surface roughness. The model predicts that the larger is the ratio σ/λ the smaller is the transmission. The theoretical results were confirmed by the experimental data.

The roughness affects the beam shape delivered by the hollow waveguide. Large roughness gives rise to higher modes of propagation which change the Gaussian shape of the laser beam.

These results helps us to understand the mechanisms that affect the transmission and improve the quality of the waveguides, making them more useful for practical applications.

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