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ABSTRACT

We have investigated the transmission characteristics of an alternative all-optical-waveguide system for x-ray delivery to a precise tissue area. The delivery system includes two basic optical elements: a funnel-shaped uncoated hollow glass taper and a flexible hollow delivery waveguide. The hollow taper provides direct launching of the input x-ray radiation into a delivery waveguide. It is an uncoated glass taper whose operating principle is based on the grazing-incidence effect. We investigated both experimentally and theoretically how the transmission properties of the hollow taper depend on its geometrical parameters such as cone shape, length, input and output core diameters. The x-ray-source-to-taper coupling efficiency obtained was about 20-25%. That is relatively low in comparison with typical laser-to-taper coupling efficiencies due to the poorly collimated x-ray beam. Furthermore, we have studied the x-ray beam profile conversion by the grazing-incidence-based hollow taper. The x-ray radiation was launched into the delivery waveguide by a direct taper-to-waveguide coupling. In our experiment, we used both uncoated and metal-coated hollow waveguides with various geometrical parameters. The waveguide transmission characteristics, including the coupling efficiencies and beam profile conversion, were investigated for both straight and bent delivery waveguides. The results obtained as presented in this report give considerable confidence for successful application of the all-waveguide system as an alternative x-ray delivery technique for biomedical use.

Keywords: X-rays, Hollow waveguides, Minimally invasive therapy

1. INTRODUCTION

Breast cancer is a terrible disease that strikes 192,000 women in the United States each year and this number will increase. A breast cancer tumor begins with a single cell that doubles in size every one hundred days. It takes approximately 9 years before it reaches a 3-5 mm size and about 11 years before it is palpable. But by the time it reaches 2 mm it may be capable of sending cancer cells into other parts of the body by metastasis through the blood vessels. This is the time that it needs to be detected and immediately irradiated - before it metastasizes. For the last six years we've been intrigued with the possibility of developing a three step approach to finding, diagnosing and irradiating tumors as early as possible. The waveguide for x-ray delivery is what we consider step three - a means of irradiating the tumor.

The steps before irradiation are 1) a high resolution time-gated femtosecond laser driven x-ray system that creates higher resolution, higher quality images by time-gating out the scattered x-rays and stereotactically locates a small tumor in three dimensions is my means of detecting tumors in the 1-2mm size. Since the images will be digitally recorded, they will be immediately available. If the x-ray shows a questionable mass, we prose to immediately insert a needle to the base of the tumor. 2) Here we propose an optical biopsy or optical diagnosis by inserting a fiber instrument down the needle to optically inspect the tumor. If it can be determined to be malignant, we propose that it immediately be irradiated either with x-rays or with a laser - and we prefer x-rays because of the ability to control depth.

We believe a system like this would be quite medically effective and also would be cost effective. In addition it would have the sensitivity of mammography and the specificity of a needle biopsy. By immediately and precisely locating and diagnosing the tumor immediately, no repeat x-ray would be necessary for later treatment. By treating the malignant tumor immediately, less risk of metastasis would be incurred. It is our belief that this would be the least costly method of screening the population. Cancer detected and treated at an early stage can be done for thousands of dollars versus hundreds of thousands of dollars to cure cancer at late-stage detection. Of course, the challenge is to find the resources to build the device and prove it.

Recently, the research efforts in practical x-ray optics is concentrated mainly on development of highly effective reflection (or so-called "super mirror"[1]) and delivery optics and waveguides. Two basic principles are exploited in these techniques: (a) multilayer[1,2] and (b) capillary[3-7] optics. The capillary x-ray systems operate through repeated total reflection of x-ray photons at the inner wall of the capillary guides The capillary optics demonstrates significant advantages such as highly effective and symmetric throughput, broad bandpass characteristics, simplicity of fabrication, and relatively low cost. Using uncoated grazing-incidence-based hollow tapers, in our previous works we have shown an alternative approach for effective laser radiation delivery. Direct laser-to-waveguide coupling works well over a wide spectral range covering the ultraviolet, visible and mid-infrared.[8-11] In this paper we report the results from the investigation of optical properties and transmission characteristics of an all-optical-waveguide system for x-ray delivery to a precise tissue area.

2. EXPERIMENT

A principal optical arrangement of the suggested all-optical-fiber x-ray delivery system is shown in Fig. 1. It is a simple single-fiber delivery technique that includes two basic optical elements: (1) a funnel-shaped uncoated hollow glass taper (or conical capillary) and (2) a delivery flexible hollow waveguide (or straight capillary). The hollow taper provides direct launching of the input x-ray radiation into a delivery waveguide. It is an uncoated glass taper whose operating principle is based on the grazing-incidence effect. In our experiment, we use a Pyrex-glass hollow taper that has the following parameters: 9-mm input core diameter, 1-mm output core diameter, 260-mm length, and a linear profile of the core radius variation along the taper length.

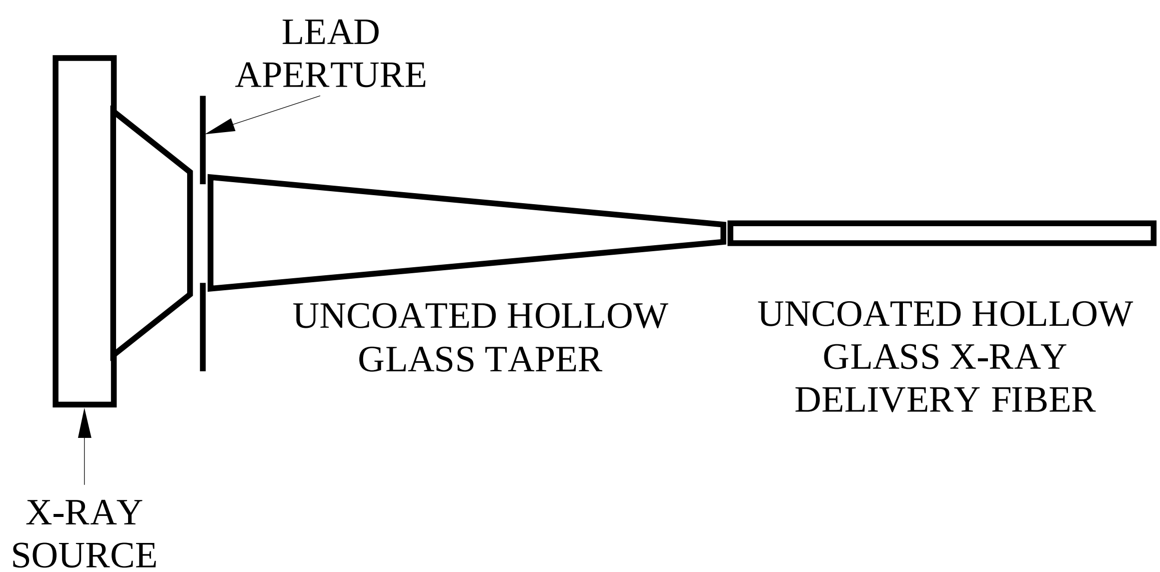

Fig. 1. Experimental setup of the all-optical-waveguide biomedical system for x-ray delivery into a precise tissue location.

The x-ray radiation is launched into the delivery waveguide by a direct taper-to-waveguide coupling. We use both uncoated and metal-coated flexible hollow waveguides with various core diameters in the range of 500-1000 micrometers. In the ideal case, the inner surface of the hollow waveguide would be as smooth as possible and can sometimes be used without any coating. Multilayer coatings can be placed on the inner wall to optimize the reflection of the walls. However, except for some experiments with liquid deposition for some materials, the vapor deposition coatings inside hollow waveguides are still not commercially available to our knowledge.

As a x-ray source in our experiment, we use a pulsed x-ray source (a Fexatron 706 200-600 keV system) that emits approximately 50 mrad of x-ray energy, producing a 3-ns burst of x-rays. To collimate our test x-ray beam, we use lead apertures with various diameters.

3. RESULTS AND DISCUSSION

Using the experimental setup presented, we investigate fundamental optical properties of the hollow-waveguide-based x-ray delivery system. Figure 2 shows an experimental arrangement for measurement of the divergence angle of the x-ray beam. In this case, the x-ray beam is collimated using an 11-mm lead circular aperture. The x-ray beam profiles, shown at the upper part of the figure, are measured at three distances from the x-ray source: 0-mm (on the surface of the collimated lead aperture), 100 mm and 200 mm. Thus, we obtain a divergence angle of the x-ray beam of 1.4 deg. Moreover, as can be seen from the x-ray beam profiles presented, the intensity distributions are relatively homogeneous and we can consider the divergence angle as the maximum angle by which the input angle to the hollow taper can be changed.

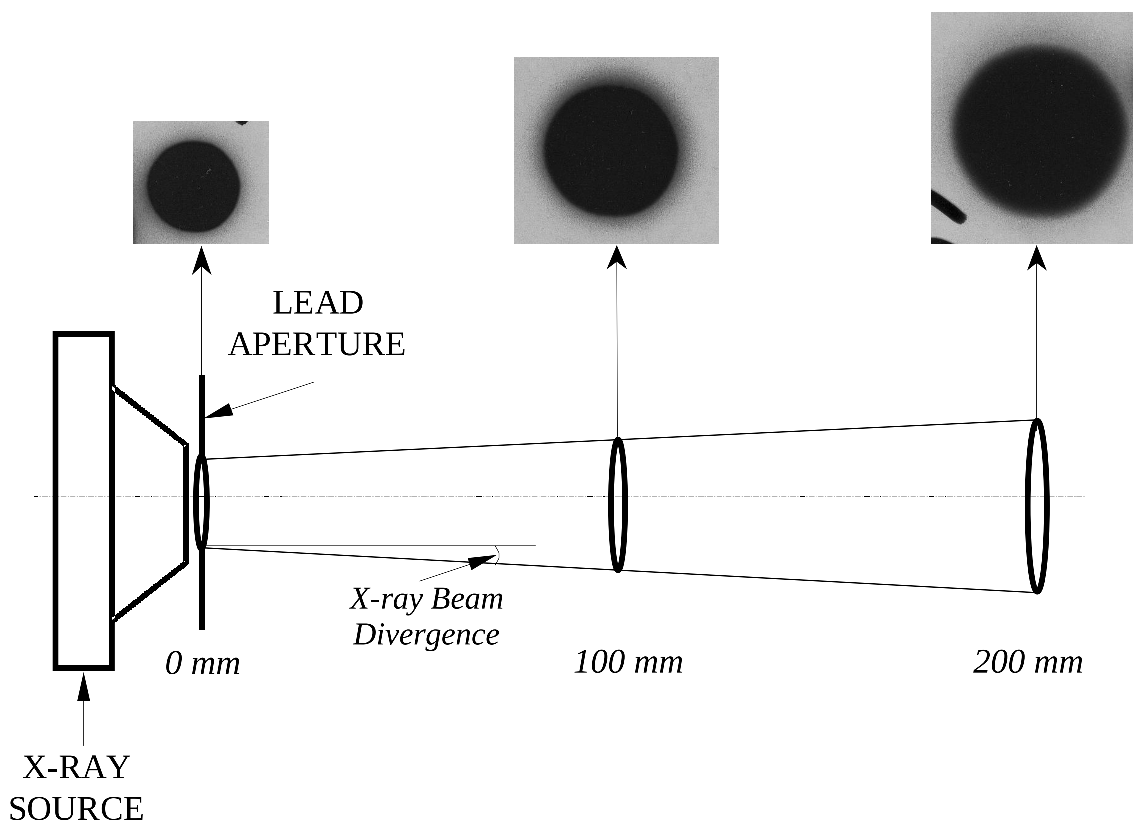

Fig. 2. Experimental setup for measurement the divergence angle of the x-ray beam.

To estimate experimentally the coupling efficiencies and transmission characteristics of the x-ray delivery system, we measure energetic parameters and intensity distributions of the input/output x-rays. Figure 3 shows the intensity

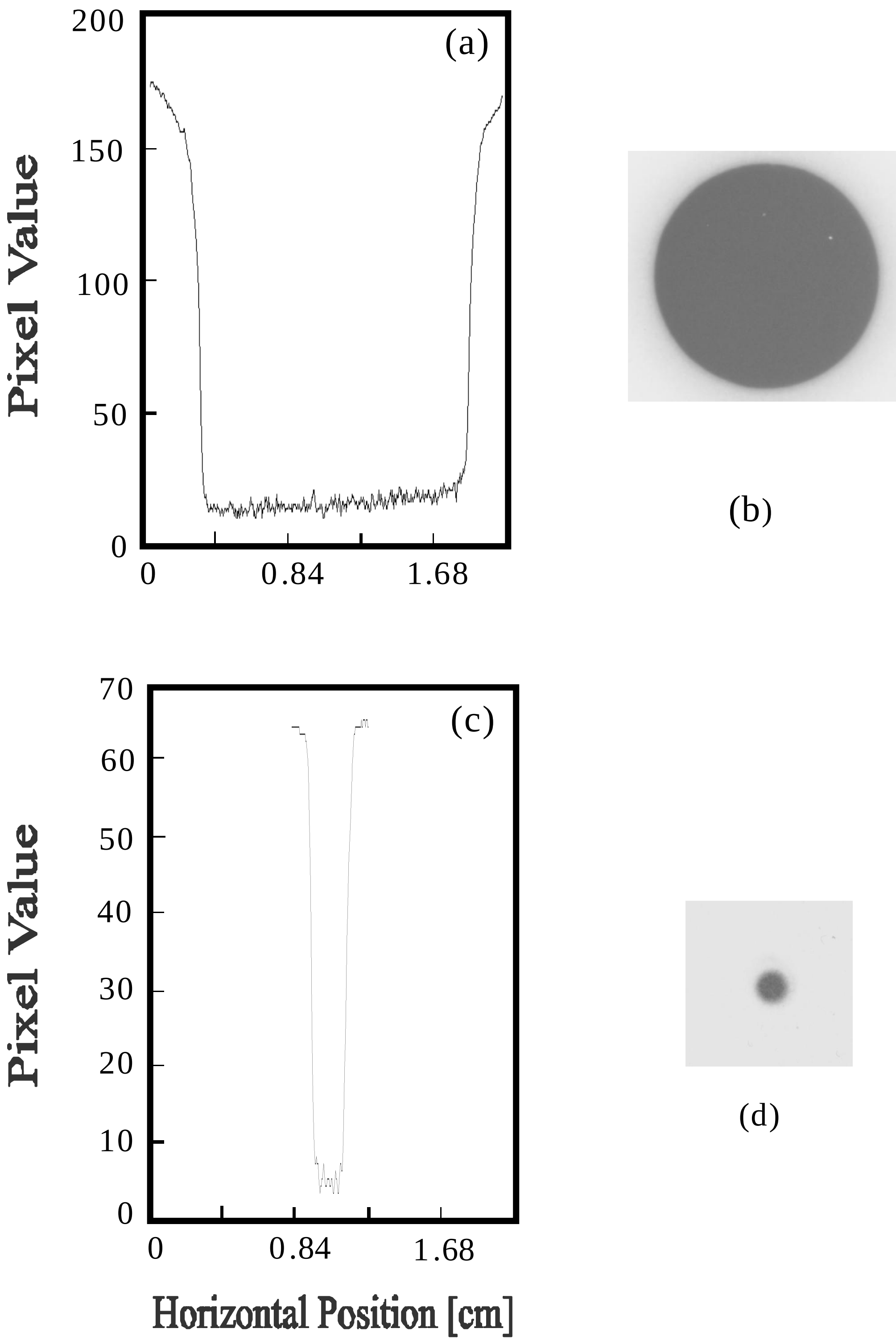

Fig. 3 X-ray intensity distributions (a, c) and beam profiles (b, d) at the input (a, b) and output (c, d) of the hollow taper.

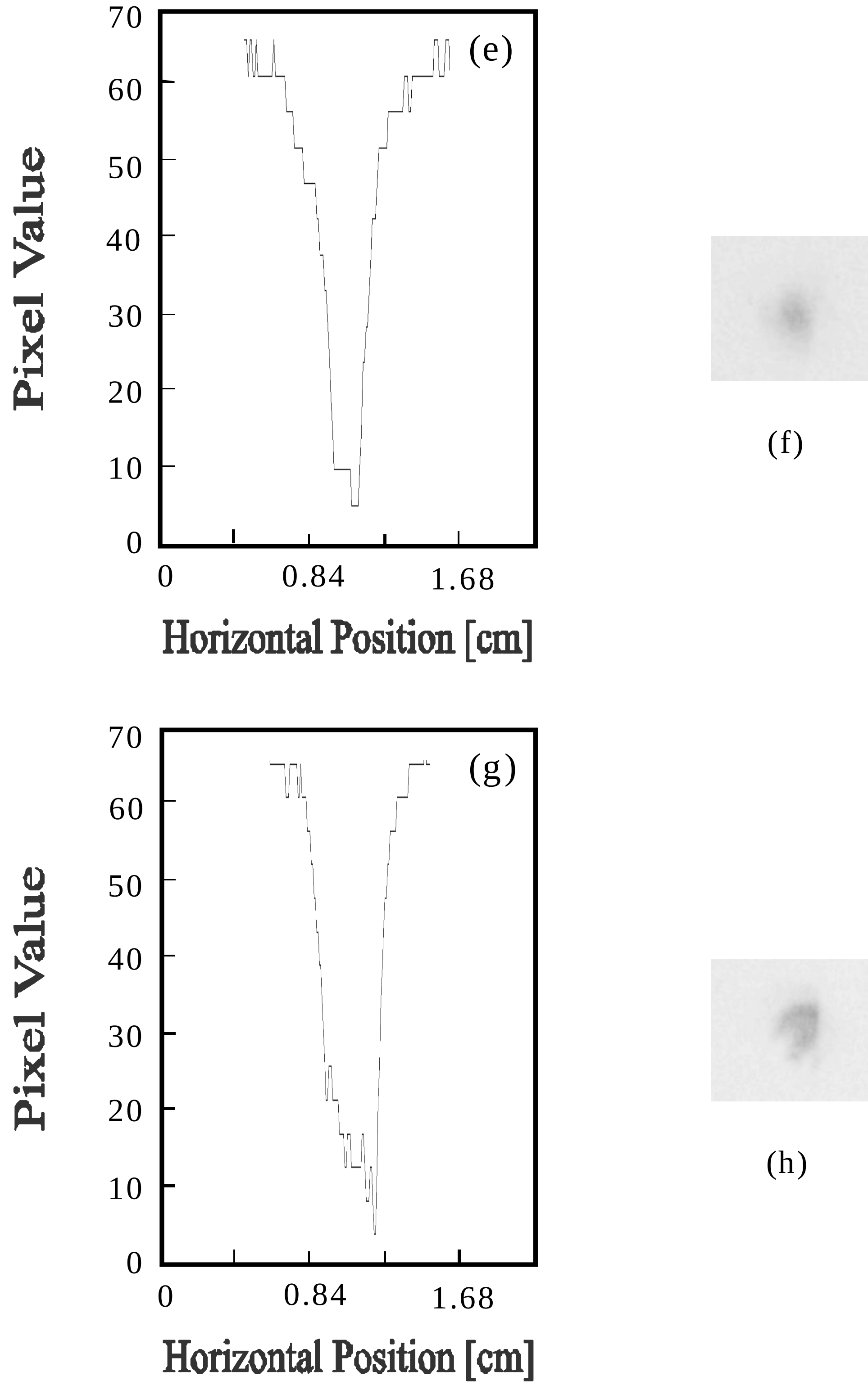

Fig. 4 X-ray intensity distributions (e, g) and beam profiles (f, h) at the output of an unbent (e, f) and bent (g, h) delivery waveguide.

distributions and beam profiles at the input (3 a, b) and output (3 c, d) of the glass hollow taper, respectively. The energy measured at the taper input and output is 5 mrads and 1.2 mrads, respectively. These energy values correspond to a x-ray-to-taper coupling efficiency of 24%. An increase of the coupling efficiency can be achieved by optimizing the taper parameters. Using a direct taper-to-waveguide coupling (see Fig. 1), the x-ray radiation from the taper output is launched into the delivery waveguide. Here, we use uncoated flexible hollow glass waveguides. Figure 4 shows intensity distributions and x-ray beam profiles registered at the end of an unbent (Fig. 4 e, f) and bent (Fig. 4. g, h) delivery waveguide, respectively. The bent angle is 15 deg. As can be seen from the beam profiles on Fig. 4 f and 4 h, while the unbent waveguide maintains the circular symmetry of the output intensity distribution, the bent waveguide introduces additional mode coupling effects and as a result, the beam profile is not symmetrical. In the case of a bent delivery waveguide, in order to stimulate more intensively waveguide mode mixing and, thus, to get more homogeneous output intensity distribution, we should use longer waveguides. Energy measured at the unbent, uncoated waveguide input and output is 1.1mrads and 0.2mrads, respectively. These measurements give us a transmission of 15 -20%. Use of good coatings on both coupler and waveguide can greatly improve the efficiency of both devices.

4. THEORETICAL MODEL

In order to simulate the x-ray beam propagation into the hollow taper as well as to estimate analytically some reflectance parameters, we apply a simple geometrical-ray method. In our case, this method is applicable because the taper air core is an absolutely homogeneous medium and the diameters of the tapers and waveguides core cross-sections are very large compared with the x-ray radiation wavelength. Figure 5 illustrates the propagation trajectory of the x-ray radiation through an uncoated hollow taper with cone angle θ.

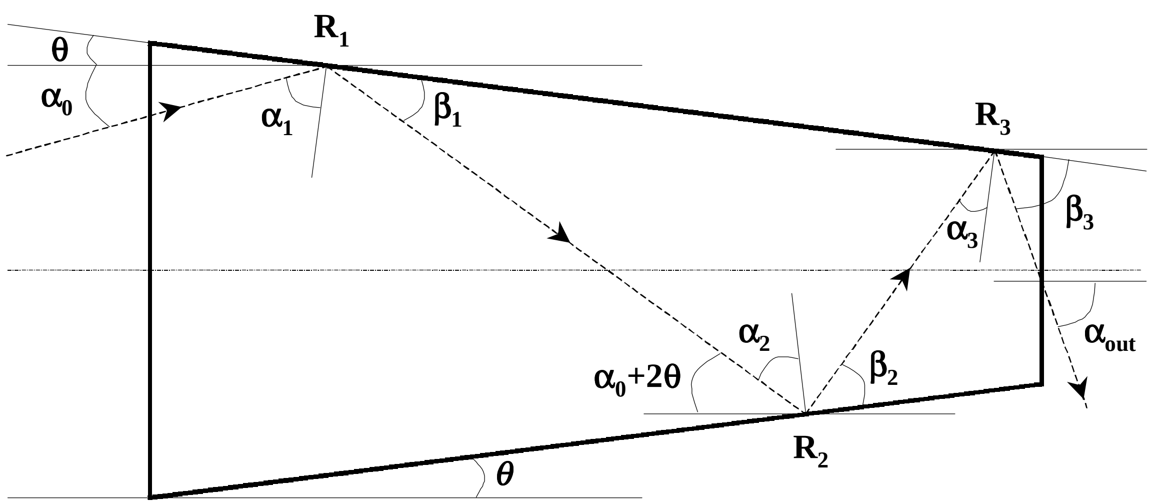

Fig. 5. Propagation of x-ray radiation through an uncoated hollow taper. θ, cone angle of the hollow taper; α_0, input angle of the input x-ray radiation; α_1, α_2, α_3, incidence angles at 1st, 2nd and 3rd reflection of the x-ray beam at the inner taper wall; β_1, β_2, β_3, glancing angles at each reflection (90 deg minus angle of incidence); α_{out}, output angle of the x-ray beam at the taper output, R_1, R_2, R_3, reflection points.

For an angle of incidence α_i at the *i*th reflection, we obtain the dependence

$$\alpha_i=90-(2i-1)\theta+\alpha_0 \quad (1)$$

where θ is the taper half-cone angle and α_0 is the input angle at the beginning of the hollow taper. For the corresponding glancing angle β_i at the *i*th reflection, a similar formula is obtained:

$$\beta_i=(2i-1)\theta+\alpha_0 \quad (2)$$

Using the theoretical model, we can calculate the x-ray propagation trajectory including the number of reflections for each ray, corresponding angles of incidence (Eq. 1) and glancing angles (Eq. 2) to the glass taper surface, and output angles at given variations of input angles. Typical analytical curves of a number of reflectances versus input angle at

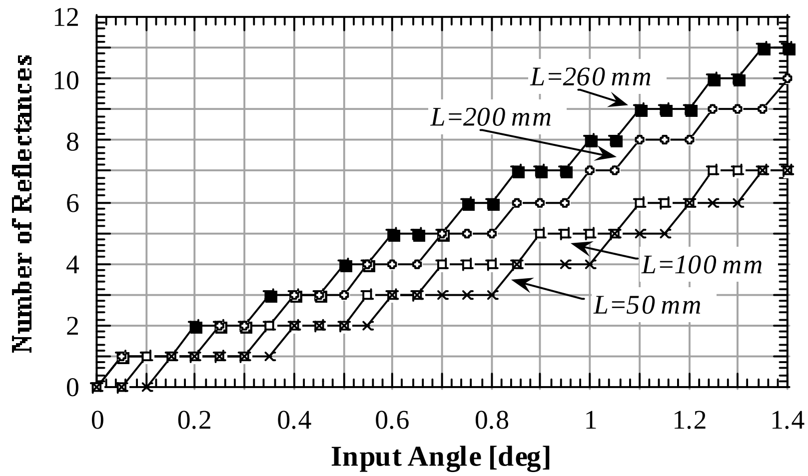

Fig. 6. Analytical dependences of number of reflectances vs. input angles at various hollow taper lengths.

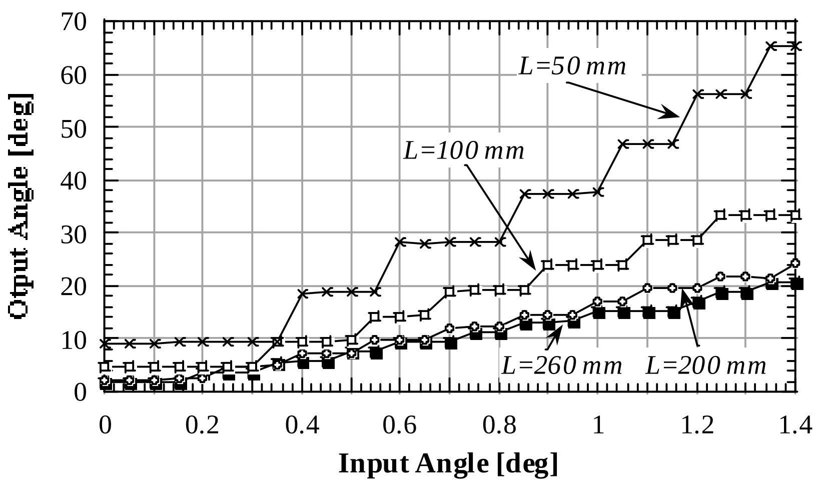

Fig. 7. Analytical dependences of output angles vs. input angles at various hollow taper lengths.

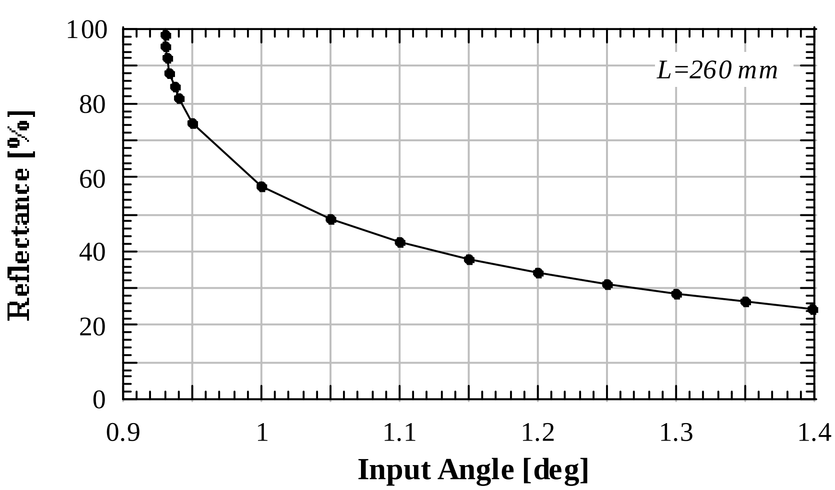

Fig. 8. Analytical dependences of reflection coefficients vs. input angles for the 260-mm long hollow taper.

various taper lengths (50, 100, 200 and 260 mm) are shown in Fig. 6. Figure 7 presents typical analytical variations of To evaluate theoretically the reflectance coefficients R_i at each reflection and therefore, the total x-ray-source-to-taper coupling efficiency, we first calculate both the angle of reflection α_i and the glancing angles β_i using the above formulas (1) and (2). Then, we calculate the angle of refraction φ_i, at each reflection using the Snell's low:

$$\varphi_i=\arcsin[\cos(\beta_I)]/n_2 \tag{3}$$

where n_2 is the complex index of refraction for x-rays. It is well know that the refractive index for x-rays is slightly less than unity and can be expressed by the formula:[7]

$$n_2=1-\delta-i\beta \tag{4}$$

where δ and β are the refractive and absorption index decrements, respectively. Finally, if we consider an unpolarized x-ray source, we can apply the Fresnel's laws of reflection expressed by the equations:[7,12]

$$R_i=[|\tan(\alpha_i-\varphi_i)/\tan(\alpha_I+\varphi_i)|^i + |\cos(\alpha_I+\varphi_i)/\cos(\alpha_i-\varphi_i)|^i]/2 \tag{5}$$

Following the simulation procedure described above, in the conditions of our experiment we can get analytical dependencies of the refraction coefficient variations while changing various parameters of the all-optical-waveguide delivery systems. Figure 8 shows a typical analytical curve of a single reflectance at the inner hollow taper wall vs. input angle of the x-ray radiation at the taper input. Using similar dependencies, we can optimize the system parameters in order to obtain the maximum x-ray transmission.

5. CONCLUSION

We have presented an alternative all-optical-waveguide technique for x-ray radiation delivery into a precise tissue area using both direct x-ray-to-taper and taper-to-waveguide coupling. The waveguide transmission characteristics, including the coupling efficiencies and beam profile conversion, were investigated for both straight and bent delivery waveguides. The results obtained as presented in this paper give considerable confidence for successful application of the all-waveguide system as an alternative x-ray delivery technique for biomedical use.

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