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Equivalent complex refractive indices for ray-tracing evaluation of dielectric-coated hollow waveguides

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Abstract. An idea of an equivalent refractive index for the ray tracing calculation of hollow core waveguides is proposed. A virtual, complex refractive index is uniquely found by minimizing the difference between reflectivity of a virtual monolayer material and a metal substrate coated with a dielectric film. By using this technique, transmission losses of a delivery system consisting of a hollow fiber and a tapered hollow waveguide are calculated. [DOI: 10.1117/1.1485090]

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To suppress the leaky loss of hollow fibers for infrared lasers, a metal hollow fiber with an inner dielectric coating has been developed.[1,2] In this fiber, the dielectric film enhances the reflection, owing to the interference effect when the optical thickness is properly designed for the target wavelength. However, the two-layered structure with a dielectric film and a metal substrate complicates the calculation using a ray-tracing method, which is useful for the design and evaluation of hollow fiber devices having relatively complicated shapes such as a tapered one.[3-5] In this letter, we introduce a concept of equivalent refractive index. We assume a virtual monolayered material having the same reflection coefficient as a dielectric-coated metal surface and use its refractive index in ray-tracing calculation. We apply this technique for the design of a tapered input coupler for hollow fibers.

Transmission losses of a hollow waveguide with an inner diameter of $2T$, which is sufficiently larger than the wavelength λ, are analyzed by using a simple ray-optic model. When the incident angle of the ray at the inner surface of the hollow waveguide is θ, the power attenuation coefficient 2α of the waveguide is[4]

$$2\alpha(\theta)=\frac{1-R(\theta)}{2T\tan\theta}, \tag{1}$$

where $R(\theta)$ is the power reflectivity at the inner wall of the waveguide. Assuming random polarization, it is expressed as

$$R(\theta)=\frac{|r_s(\theta)|^2+|r_p(\theta)|^2}{2}, \tag{2}$$

where $r_s(\theta)$ and $r_p(\theta)$ are reflection coefficients of s- and p-polarized light, respectively.

We assume a metal surface coated with a dielectric film having a thickness of d. The refractive index of metal is a complex number $\nu=n-jk$ and the index of the dielectric film is a. The reflection coefficients $r_s(\theta)$ and $r_p(\theta)$ of the coated metal surface are usually calculated considering the interference effect of the coating, which increases calculation time in ray-tracing evaluation. Therefore, here we consider a virtual monolayer material with a refractive index of $\nu_e=n_e-jk_e$ having the same reflectivity $R(\theta)$ of the coated metal surface. The reflection coefficients $r'_{s,p}(\theta)$ of the virtual materials are similar to those of the metal surface[6]:

$$r'_{s,p}(\theta)=\begin{cases}\dfrac{\cos\theta-\sqrt{\nu_e^2-\sin^2\theta}}{\cos\theta+\sqrt{\nu_e^2-\sin^2\theta}}\\[2ex]\dfrac{\nu_e^2\cos\theta-\sqrt{\nu_e^2-\sin^2\theta}}{\nu_e^2\cos\theta+\sqrt{\nu_e^2-\sin^2\theta}}\end{cases}. \tag{3}$$

We first apply this idea to a silver substrate coated with a cyclic olefin polymer (COP) film. The refractive indices at the CO_2-laser wavelength of 10.6 μm are $\nu=13.5-j75.2$ for silver and $a=1.53$ for COP. The optimum thickness of the COP film for 10.6 μm wavelength is 1.37 μm.

At the inner wall of the hollow fibers, the incident angle of transmitted light is usually very large (80 to 90 deg), and even in tapered waveguides, the incident angle is larger than 60 deg. Therefore, to find $\nu_e=n_e-jk_e$, we minimize the difference δ between reflectivity of the real model R_θ and the virtual model R'_θ:

$$\delta=\sum_{\theta=60^\circ}^{90^\circ}|R_\theta-R'_\theta|^2. \tag{4}$$

Figure 1 shows a plot of calculated δ for various combinations of n_e and k_e. The smallest δ value is uniquely found and in this case, it is $\nu_e=0.0158-j1.71$, which gives $\delta=8\times10^{-8}$. Figure 2 shows reflectivity versus incident angle for the Ag substrate coated with the COP film. Curve (a) shows an exact calculation and curve (b) is calculated by using the virtual model. It is shown that these two plots agree very well for the incident angles larger than 60 deg.

We apply the equivalent refractive-index method to the ray-tracing calculation of transmission losses of a hollow-waveguide delivery system that includes a tapered input coupler. The system consists of a 1-m-long, hollow-core fiber with an inner diameter of 0.7 mm and a tapered hollow waveguide with a length of L and an inner diameter of 0.7 mm at the output end. The fiber is butt-coupled to the output end of the tapered waveguide. We consider a linear

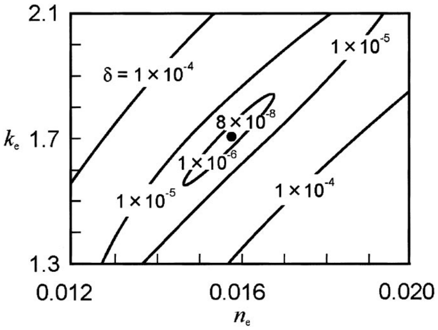

Fig. 1 Contour plot of reflectivity difference δ between the real and the virtual models of the Ag substrate coated with the COP film.

tapered waveguide having a silver inner layer coated with a COP film whose thickness is optimized at a 10.6-μm wavelength, which is 1.37 μm. As an input beam, we assume a focused beam that has a Gaussian profile with a spot diameter of 0.3 μm. For the calculation, we used a commercial software program, OptiCAD.

Figure 3 shows the losses of the delivery system, which are calculated by changing the length and the inner diameter of the input end of the taper waveguide D_{in}. We find that the optimum taper shape is obtained with the parameters $D_{\mathrm{in}} = 1.1$ mm and $L = 90$ mm. For the fastest taper in this figure ($D_{\mathrm{in}} = 1.2$ and $L = 10$ mm), our ray tracing shows that the minimum incident angle is around 87 deg where discrepancy of reflectivity between the real and equivalent models is as small as 1.4×10^{-6}. To check the advantage of faster calculation, we compared the calculation time of the equivalent model to that of the real models by using a simple 2-D ray tracing. The result shows that the presented model shortens the calculation time by more than a factor of three.

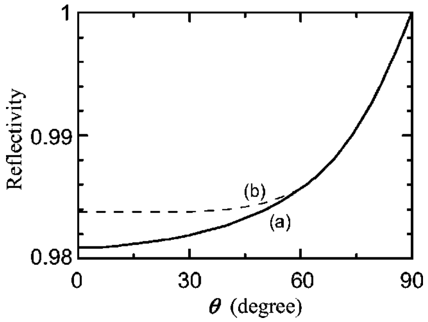

Fig. 2 Reflectivity of a COP-coated silver surface for (a) exact calculation and (b) calculation using the virtual complex index.

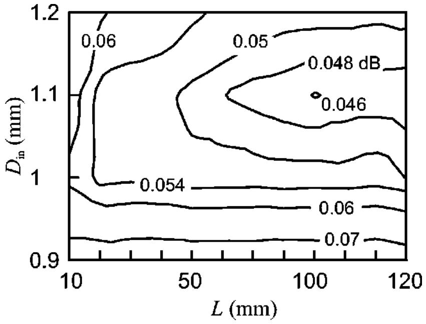

Fig. 3 Plot of calculated losses of the delivery system composed of a hollow fiber and a tapered hollow waveguide.

In conclusion, we proposed the idea of an equivalent refractive index for ray tracing calculation of hollow-core waveguides. A virtual, complex refractive index is uniquely found by minimizing the difference between reflectivity of a virtual monolayer material and a metal substrate coated with a dielectric film. By using this technique, we calculated transmission losses of a delivery system composed of a hollow fiber and a tapered hollow waveguide. Evaluation of hollow waveguides having an inner multilayer film and a complex shape is easily performed by employing this method.

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