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Filtering and Transmission Characteristics of Optical Wave in Lattice Grid with Lossy Clad for Optical CT

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***Abstract*—In medical image diagnosis using optical waves of laser, image responses of optical transmitted projection include optical scattering characteristics that disturb transmission properties through biological structures depending on optical absorption effects. We have studied spatial filtering by lossy grid array for optical scattering superposed on transmitted and attenuated waves to improve image diagnosis. In this paper, reflection and transmission characteristics of waveguide-type spatial filter are studied by FDTD method, comparing with approximate analytical method for optimum design of spatial filter.**

I. Introduction

Medical image diagnosis using optical waves of lasers is very important technical tools for physiological examination of human body. Image responses of optical transmitted projection include optical scattering characteristics that disturb transmission properties through biological structures depending on optical absorption effects due to biological characteristics consisting of atomic and molecular structure [1]-[5]. We have studied spatial filtering by lossy grid array for optical scattering superposed on transmitted and attenuated waves to improve image diagnosis[6]-[9]. Spatial filtering characteristics of lossy grid structure are shown for exact image optical projection excluding scattering effects through physiological media by FDTD method. In waveguide-type grid filters with lossy clads, scattered fields from biological structures with large scattering angles have large attenuations. Transmitted and scattered fields of small scattering angles have small attenuations and can pass through the waveguide grids. We studied statistical scattering characteristics of biological objects surrounded by inhomogeneous biological media using FDTD method and showed that spatial filtering by waveguide-type grid filter with lossy clads is very effective to suppress scattered waves with large scattering angles and to obtain accurate target object image.

In this paper, reflection, transmission and filtering characteristics of waveguide-type spatial filter consisting of clad and core with relatively long length and complex refractive index of lossy clad for incident angles of the incident beam are studied by FDTD method, comparing with approximate analytical method, such as physical and geometrical optics, for optimum design of structure of spatial filter to accomplish accurate image diagnosis by optical CT. Fig. 1 shows the FDTD analysis model for lattice grid with width of lossy clad d, width of transparent core D, length of grid ℓ_g and complex refractive index n_g^*. The amplitudes of transmitted and attenuated waves in core and clad regions are evaluated. For large incident angles of the incident beam, attenuation of the amplitudes of transmitted waves become large due to the absorption by lossy clads and realization of effective spatial filter is expected. In this study, electric field distributions in waveguide-type grids are shown precisely using FDTD method. Also, field distributions are studied by approximate analytical method which gives physical interpretation for numerical results obtained by FDTD. The numerical and analytical methods can provide optimum design of lossy lattice grid spatial filter with desired performance for accurate image diagnosis by optical CT.

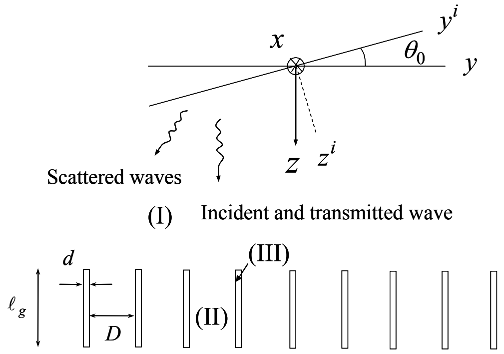


Fig.1 Lattice grid for optical CT

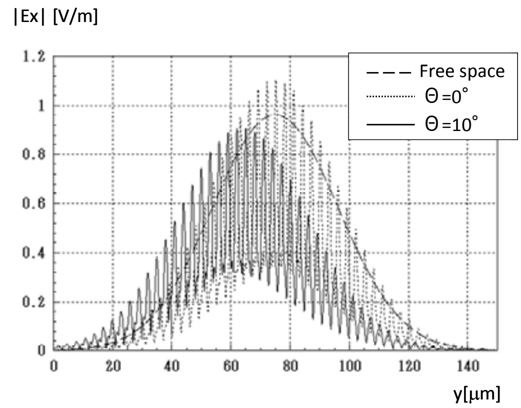


Fig.2 Electric field amplitude at z =100μm, θ=0, 10°

Fig.2 shows the amplitudes of transmitted electric field at z=100μm, when Gaussian beam with beam spot size 30μm is incident to lossy grid with d =0.5μm, D =2.5μm, ℓ_g =10μm and n_g^* =2-j0.5. When the incident angle θ corresponding to scattering angle in optical CT is larger than $\theta = 10^\circ$, the amplitude of transmitted wave is attenuated due to the absorption of lossy clads of lattice grid.

II. Reflection and Transmission Characteristics of Grid Wall

For fundamental study on reflection and transmission of optical wave by lossy grid, reflection and transmission coefficients of the incident plane wave on the interfaces of core and clad are evaluated. In Fig.1, we define region I of free space, region II of core of grid with refractive index n_1 and region III of lossy clad with complex refractive index $n_2 = n_{r2} - jn_{i2}$. Wave numbers are $k_1 = k_0 n_1$ in regions I and II, and $k_2 = k_0 n_2$ in region III, where $k_0 = 2\pi/\lambda$ is wave number and λ is wavelength in free space.

Fresnel reflection and transmission coefficients R and T of TE waves are, when the plane wave incident from region II to region III

$$R = \frac{\cos\theta_i - \sqrt{n^2 - \sin^2\theta_i}}{\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}}, \quad T = \frac{2\cos\theta_i}{\cos\theta_i + \sqrt{n^2 - \sin^2\theta_i}} \qquad (1)$$

where $n = \frac{n_t}{n_i}$, $n_i = n_1$, $n_t = n_2$. In case the plane wave incident from region III to region II, $n = \frac{n_t}{n_i}$, $n_i = n_2$, $n_t = n_1$, $|n_2| > |n_1|$ and for incident angles $\theta_i > \theta_c$, incident waves are reflected as total reflection, where critical angle θ_c is

$$|n| = \left|\frac{n_1}{n_2}\right| = \sin\theta_c < 1 \qquad (2)$$

Fig. 4, 5 and Fig. 6 show reflection and transmission coefficients for incident angle $\theta_i' = \frac{\pi}{2} - \theta_i$ when $n_1 = 1$ and $n_2 =$ $2 - j0.05$, $1.5 - j0.05$.

III. Refrection and Transmission Characteristics of Lattice Grid by Kirchhoff-Huygens Equation

Far electromagnetic field can be approximately studied by Kirchhoff-Huygens equation. We consider two-dimensional problem of incident x-polarized plane wave in yz plane. We define A and B for the boundary between region I and II, III. Using Green's function in two-dimensional free space

$$G(\mathbf{r},\mathbf{r}') = -\frac{j}{4}H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) = -\frac{j}{4}H_0^{(2)}(k\rho) \qquad (3)$$

where, $\rho = |\mathbf{r}-\mathbf{r}'| = \sqrt{(y-y')^2 + (z-z')^2}$.

for the incident plane wave with propagation angle θ_0, far field is

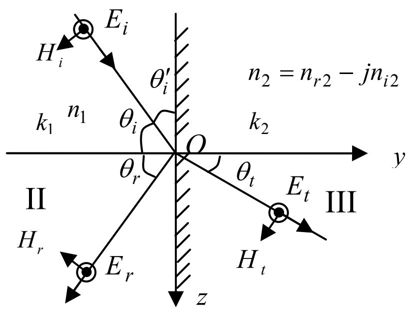


Fig.3 Reflection and transmission of plane wave in case of TE incidence.

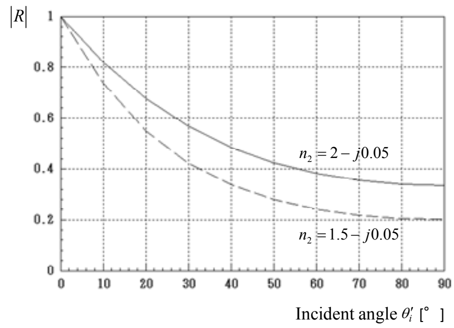


Fig.4 Reflection coefficient when the wave incident from region II to region III.

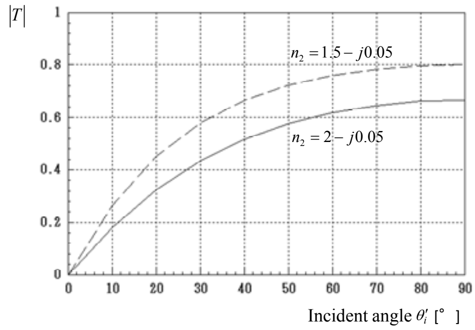


Fig.5 Transmission coefficient when the wave incident from region II to region III

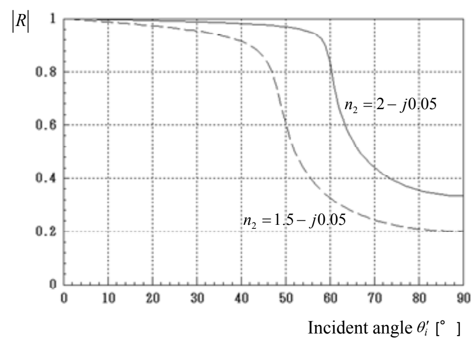


Fig.6 Reflection coefficient when the wave incident from region III to region III.

$$E_x(y,z)=\sqrt{\frac{k}{8\pi}}e^{j\frac{\pi}{4}}\int_S\left(\cos\theta_0+\cos\theta_\rho\right)\frac{e^{-jk\rho}}{\sqrt{\rho}}E_x^{(0)}(y')dy' \quad (4)$$

where, $\cos\theta_\rho=\dfrac{z-z'}{\rho}$ and $E_x^{(0)}(y')$ is the electric field on the surface A and B given by incident wave. In case of $\cos\theta_0\approx 1$ and $\cos\theta_\rho\approx 1$,eq.(4) is

$$E_x(y,z)=\sqrt{\frac{k}{2\pi}}e^{j\frac{\pi}{4}}\int_S\frac{e^{-jk\rho}}{\sqrt{\rho}}E_x^{(0)}(y')dy' \quad (5)$$

Reflected and scattered fields in region I are obtained by $E_x^{(0)}=RE_y^{(inc)}$ on surface B using $k=k_0n_1$ and reflection coefficient of grid wall R . Electric field in region II is obtained by $E_x^{(0)}=E_x^{(inc)}$ using $k=k_0n_1$ as radiated field from source field on A. Electric field in region III is obtained by $E_x^{(0)}=TE_x^{(inc)}$ on B using $k=k_0n_2$ and transmission coefficient of grid wall T .

IV. FDTD Analysis of Lattice Grid Characteristics

Filtering characteristics of optical wave by lattice grid are analysed by FDTD method. Fig. 7 shows the analysis model for lattice grid. Incident wave is assumed to be generated by equivalent current at z=z$_0$ (j=1),

$$J_x^n(i,1)=J_0\left\{\frac{1}{1+e^{-u(i\Delta s\cos\theta_0-y_1)}}+\frac{1}{1+e^{u(i\Delta s\cos\theta_0-y_2)}}-1\right\} \quad (6)$$
$$\cdot\left\{\frac{1}{1+e^{-w(n\Delta t-t_1)}}+\frac{1}{1+e^{w(n\Delta t-t_2)}}-1\right\}\sin\left\{2\pi\left(fn\Delta t-(i\Delta s-y_0)\sin\theta_0/\lambda_0\right)\right\}$$

where θ_0 is the incident angle. For grid structure, width of lossy clad d =1μm with complex refractive index n_g^* =2-j0.05, core width D =20 μm, length ℓ_g =40 μm are considered. Using the model shown in Fig. 7, reflected and transmitted electric field amplitude in and out of grid space for $\theta_0=0,10^\circ$ at z=0-50μm are shown in Fig. 8 - 10. Comparison of results by FDTD and approximate analytical theory is shown in Fig.11-13. As shown in Fig. 8, the electric

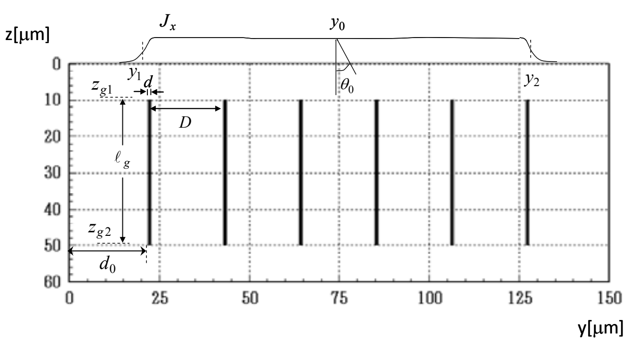


Fig. 7 FDTD analysis model for lattice grid
n_g^*=2.0-j0.05, d=1μm, D=20μm, lg=40μm,
d$_0$=22μm, zg$_1$=10μm, zg$_2$=50μm

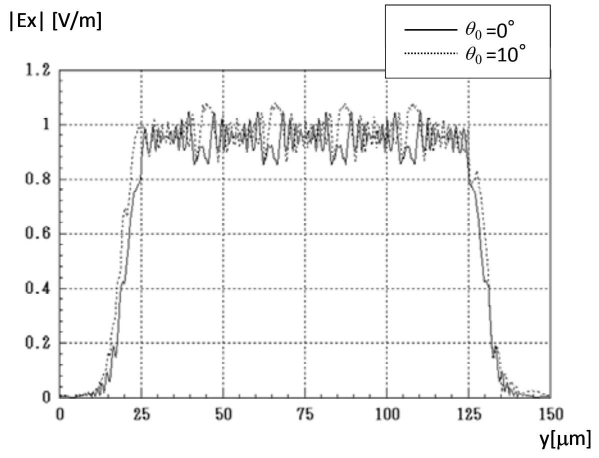
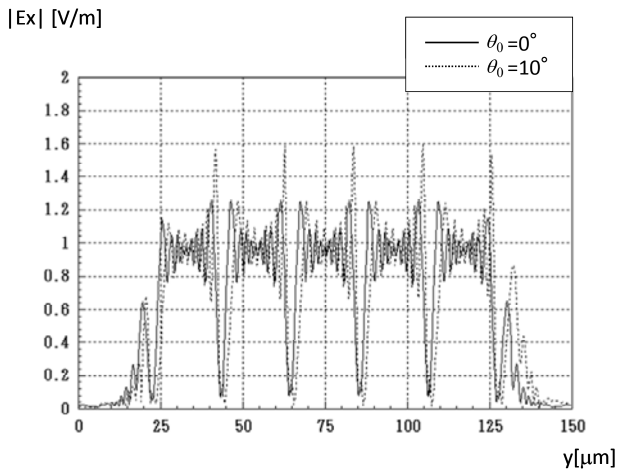
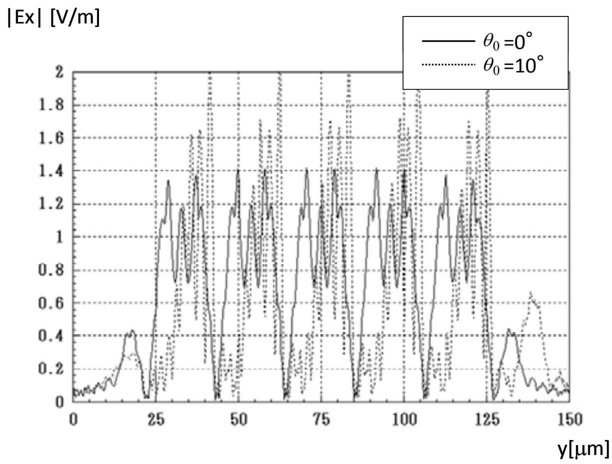


Fig.8 Transmitted electric field amplitude in region I at z=0μm by FDTD analysis



(a) z=20μm



(b) z=50μm

Fig.9 Transmitted electric field amplitude by FDTD analysis field amplitude in region I is complicated distribution when $\theta_0 = 0,\ 10^\circ$, due to the interference in the incident, reflected and diffracted waves. Fig.9 shows attenuated amplitude fluctuation after long propagation distance z . As shown in Fig.10, electric field in region III is strongly attenuated due to the absorption of lossy clad. Fig. 11 and 12 of transmitted

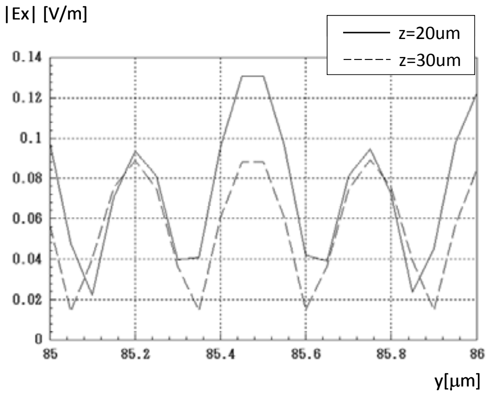


Fig.10 Attenuated electric field amplitude in region III by FDTD analysis

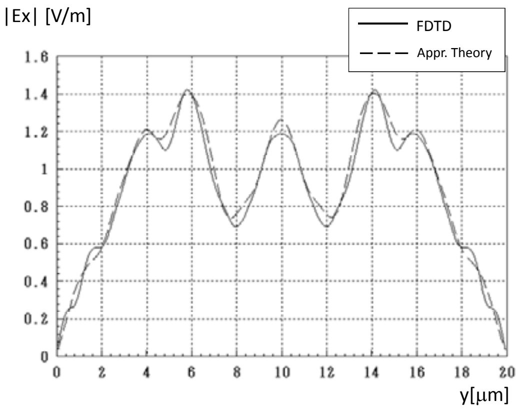


Fig.11 Comparison of transmitted electric field at z=50μm in region II, θ_0=0°

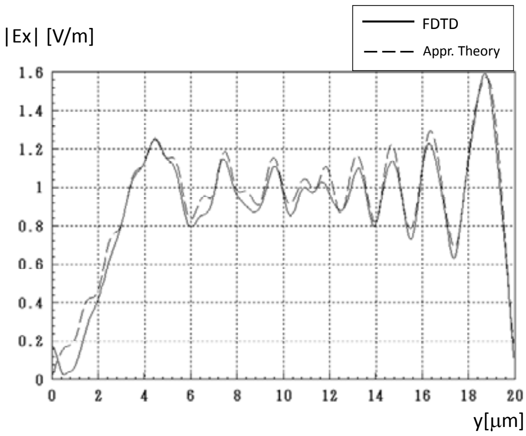


Fig. 12 Comparison of transmitted electric field at z=20μm in region II, θ_0=10°

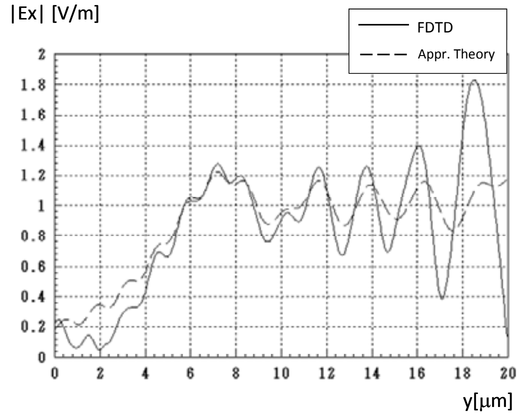


Fig. 13 Comparison of transmitted electric field at z=30μm in region II, θ_0=10°

field show relatively good agreement among FDTD results and approximate analytical results using Kirchhoff – Huygens equation, in case reflection from grid wall is very weak. When there are scattering objects and $\theta_0 = 0^\circ$, scattered waves with scattering angle more than 30° are filtered by lossy grid with grid distance 20μm and length 40μm.

V. Conclusion

In this paper, reflection and transmission characteristics of waveguide-type spatial filter consisting of clad and core with relatively long length are studied by FDTD method, comparing with approximate analytical method based on Kirchhoff-Huygens equation. For large incident angles of the incident beam, attenuation of the amplitudes of transmitted waves become large due to the absorption by lossy clads and realization of effective spatial filter is expected.

References

[1] Y. Miyazaki, "Light Scattering of Laser Beams by Random Micro-Inhomogeneities in Glasses and Polymers, " Jpn. Jour. Appl. Phys.,Vol.13, pp.1238-1248, 1974.
[2] Y. Miyazaki, "Spatial Filtering of Optical Scattered Waves in Bio-Medical Media By Inhomogeneous Waveguide Grids For Optical CT, " Proc. of APMC 2007, Bangkok, pp.527-530, 2007.
[3] Y. Miyazaki and K. Kouno, "FDTD Analysis of Spatial Filtering of Scattered Waves for Optical CT of Medical Diagnosis," IEEJ Trans. FM, Vol.129, No.10, pp.693-698, 2009.
[4] J. M. Schmitt, "Optical Coherence Tomography (OCT): A Review," IEEE Selected Topics in QE, Vol.5, No.4, pp.1205-1215, 1999.
[5] W.F. Cheong, S.A. Prahl and A.J. Welch, "A Review of the Optical Properties of Biological Tissues," IEEE Jour. QE, Vol.26, No.12, pp.2166-2185, 1990.
[6] Y. Miyazaki, "Partially Coherent Optical Waves in Random Gradient Fibers," Optical and Quantum Electronics, Vol.9, pp.153-165, 1977
[7] Y. Miyazaki, "Electromagnetic Characteristics of Grid Structures for Scattering Fields of Nano-meter Electromagnetic Waves and X-rays," Proc. of PIERS 2006, Tokyo, pp.543-547, 2006
[8] Y. Miyazaki and K. Takahashi, "Computer Simulation of X-Ray Scattering Characteristics for Medical Image Diagnosis," Trans. IEE Japan, Vol.126-C, No.12, pp.1431-1440, 2006.
[9] K. Takahashi, Y. Miyazaki and N. Goto, "FDTD Parallel Computational Analysis of Grid-Type Scattering Filter Characteristics for Medical X-ray Image Diagnosis", IEEJ Trans. EIS, Vol.127, No.12, pp.1973-1981, 2007.