

Tunability of nonuniform reflection holographic filter

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The tunability of nonuniform reflection holographic filter is investigated theoretically and experimentally. It is shown that the reflection holographic filter has not only high optical density and narrow bandwidth, but also good tunability. The coupled wave theoretical model for uniform medium is compared with the model for nonuniform medium. It is identified that the coincidence of the theoretical results of the nonuniform model with the experimental results are better than that of the uniform model.

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Optical filters play an important part in many science fields, especially in lasers and optical communications. The reflection holographic filter is a kind of novel optical filters. It has narrow bandwidth, high optical density, and good tunability etc. In recent years, the studies and application of reflection holographic filter were often reported both in theory and experiments^[1-4]. Kogelnik, Kubota and D. H. Liu provided different models and analyzed the characteristics of the reflection holographic filter. Kaiser Co. of USA has reported narrow-band reflection holographic filter is difficultly acquired in experiments^[5]. In this paper, the diffractive characteristics of dichromated gelatin (DCG) reflection holographic filter^[6] are analyzed by using Kubota's method. The tunability of reflection holographic filter is investigated theoretically and experimentally. The coupled wave theoretical models for uniform medium and nonuniform medium are compared and analyzed.

The nonuniform structure for diffraction of a reflection hologram is shown in Fig. 1.

The fringe plane of the reflection hologram parallels to the medium surface and is perpendicular to z -axis. The modulation of refractive index n_1 and the period of fringe d are function of z . T is the thickness of DCG layer. θ_c and θ_i are the angles of incidence and diffraction respectively, and $\theta_i = \pi - \theta_c$. n_0 is the refractive index and λ is the wavelength of free space.

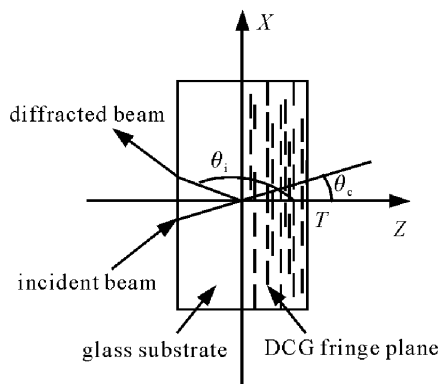


Fig. 1. Nonuniform structure for diffraction of a reflection hologram.

The incidence wave u_c and the diffraction wave u_i are respectively expressed as

$$u_c = R(z) \exp[-i(k_c \cdot r)], \quad (1)$$

$$u_i = S(z) \exp[-i(k_i \cdot r)], \quad (2)$$

where, $R(z)$ and $S(z)$ are complex amplitudes. k_c and k_i are the transmit vectors of u_c and u_i . The relationship between k_c and k_i is shown in Fig. 2. k_o and k_r are the transmit vectors of object and reference light respectively.

The coupled wave equations are obtained by using Kogelnik's method^[1,7]

$$\cos \theta_c \frac{dR(z)}{dz} = -ik(z)S(z) \exp[i\psi(z)], \quad (3)$$

$$\cos \theta_i \frac{dS(z)}{dz} = ik(z)R(z) \exp[-i\psi(z)], \quad (4)$$

where, $k(z)$ is the coupling coefficient and $\psi(z)$ is the phase shift. If

$$\rho(z) = S(z)/R(z) \exp[i\psi(z)], \quad (5)$$

then, Ricatti equation is^[2,7]

$$\frac{d\rho}{dz} = i\rho \frac{d\psi}{dz} + ik(1 + \rho^2)/\cos \theta_c. \quad (6)$$

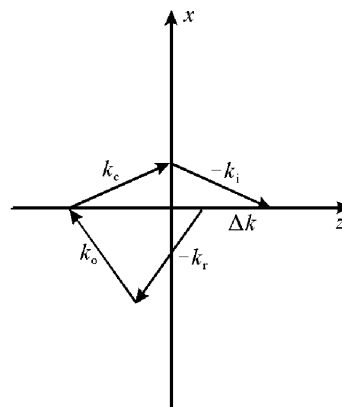


Fig. 2. Relationship between the vectors of recording wave and diffracting wave.

For uniform medium, the modulation of refractive index n_1 and the fringe period d are constants, so the coupling coefficient k and the deviation phase ψ are respectively

$$k = \pi n_1 / \lambda, \tag{7}$$

$$d\psi/dz = \Delta k. \tag{8}$$

For nonuniform medium, the models of the modulation of refractive index $n_1(z)$ and phase shift ψ are^[6,7]

$$n_1(z) = n_1(T) \left[(1-p) \left(\frac{z}{T} \right)^r + p \right], \tag{9}$$

$$\frac{d\psi}{dz} = \Delta k - K \left[G(0) - \Delta G \left(\frac{z}{T} \right)^s \right], \tag{10}$$

where, T is the thickness of medium. The surface of medium is perpendicular to z -axis. $z = 0$ locates at the interface of the medium layer and the glass substrate and $z = T$ locates at the interface of the medium layer and the epoxide resin layer. $p = n_1(0)/n_1(T)$ indicate the ratio of the modulations of two medium surfaces. $G(0)$ is the difference of relative average space frequency at $z = 0$, ΔG is the maximum of the relative difference of space frequency. r and s are the power numbers of the modulation of refractive index $n_1(z)$ and the phase shift ψ , respectively.

According to the two models and the boundary condition $\rho(T) = 0$, the diffractive efficiency is obtained by using Runge-Kutta method

$$\eta = \rho(0)\rho^*(0). \tag{11}$$

Finally, we obtained diffraction curves and calculate peak wavelength and bandwidth with the two models.

Figure 3 is the optical system for recording reflection holograms. In Fig. 3, S. F., L , DCG, and M are the space filter, collimating lens, DCG medium, and mirror, respectively. For avoiding interference fringe on the DCG surface. We put the recording film and the mirror into a matching box (shown in Fig. 3 by dashed). The matching solution is xylene.

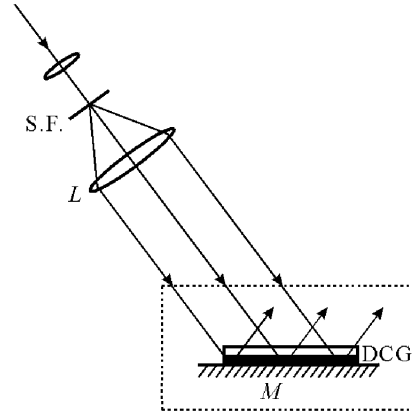


Fig. 3. Optical system for recording reflection holograms.

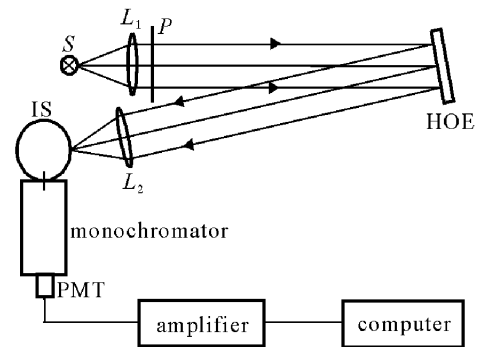


Fig. 4. Measurement system for diffraction efficiency of reflection holograms. S: source; P: polarimeter; L_1, L_2 : lens; IS: integral sphere.

The recording wavelength is 514.5 nm of argon ion laser. Interference fringes parallel to the DCG surface. The thickness of the DCG is 32 μm . Then the reflective holographic filter is fabricated^[8].

Figure 4 gives the system for measuring the diffraction efficiencies of reflection hologram. The optical segment of the measurement system is set on a rotational optical stand. Before measurement, take off holographic optical element (HOE) first, make the two arms of the optical stand to be a beeline, and scan the spectrum of the light

Table 1. Comparison of Experimental and Theoretical Data of Tunability of the Reflection Hologram

θ (deg.)	Experimental Data			Theoretical Data (a)			Theoretical Data (b)		
	λ_f (nm)	$\Delta\lambda$ (nm)	η	λ_f (nm)	$\Delta\lambda$ (nm)	η	λ_f (nm)	$\Delta\lambda$ (nm)	η
$\sqrt{22}$	669.7	45.4	—	666.4	17.4	0.999604	667.2	42.2	0.999574
26	652.2	46.3	—	648.9	17.7	0.999761	649.6	43.6	0.999742
30	632.6	47.1	0.999928*	629.9	18.1	0.999868	630.6	45.1	0.999857
$\sqrt{34}$	612.4	48.4	—	609.4	18.4	0.999935	610.2	47.1	0.999929
38	588.2	49.7	—	587.6	18.9	0.999972	588.2	49.1	0.999969
42	565.2	51.3	—	564.4	19.5	0.999989	565.1	51.6	0.999991
$\sqrt{46}$	540.8	53.2	—	540.2	20.2	0.999997	540.6	54.3	1.000000
50	514.6	55.7	0.999999**	514.7	20.9	0.999999	515.2	57.4	1.000000
54	488.2	58.4	—	488.4	21.8	1.000000	488.8	61.0	1.000000
$\sqrt{58}$	468.6	59.9	—	461.2	22.9	1.000000	461.6	65.1	1.000000

Noting: the curves of data with ticks are given. (a) For uniform medium; (b) For nonuniform medium. * Measured at 632.8 nm and ** at 514.5 nm.

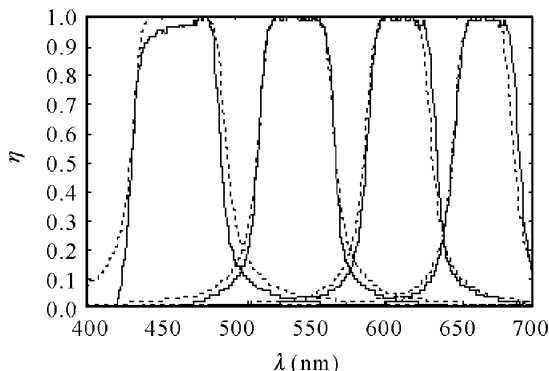


Fig. 5. Experimental and theoretical curves of tunability of the reflection hologram. The solid line is experimental curve. The dash line is theoretical curve of nonlinear medium.

source, then test diffractive signal according to Fig. 4.

The diffraction curves of HOE at different reconstruction angles are calculated with the two theoretical models of uniform medium and nonuniform medium, respectively. The peak wavelength and the bandwidth are also given and compared with the experimental results. The experimental and theoretical data are both shown in Table 1. Some of them are shown in Fig. 5 schematically.

We obtained diffractive efficiency by measuring the transmission intensity. We tested the transmission of HOE at 632.8 nm of He-Ne Laser and 514.5 nm of argon ion laser. They are 0.000084 and 0.000001, respectively. Thus we calculated diffractive efficiency at 632.8 and 514.5 nm are 0.999916 and 0.999999, respectively. The transmission is less than 10^{-6} when the wavelength is less than 514.5 nm. We can't obtain the accurate transmission for the limitation of experiment condition. So we only give the diffractive efficiency at 632.8 and 514.5 nm.

We also compare the curves of experimental and theoretical results of peak wavelength and bandwidth at different reconstruction angles, which are shown in Figs. 6 and 7, respectively. From Figs. 6 and 7, we find that the calculated peak wavelengths are identical with the experimental ones. It indicates that Bragg condition is still meet in the coupled wave theory for nonuniform medium. But the calculated bandwidths for uniform medium by the coupled wave model are inconsistent with the experimental ones. On the other hand, the calculated bandwidths for nonuniform medium are generally coincident with the experimental ones. It proves that the rationality of the coupled wave theoretical model for nonuniform medium.

In summary, the tunability of reflection holographic filter is studied theoretically and experimentally. It is shown that the reflection holographic filter has good tunability over the whole visible spectrum. Theoretical calculations are in good agreement with experimental

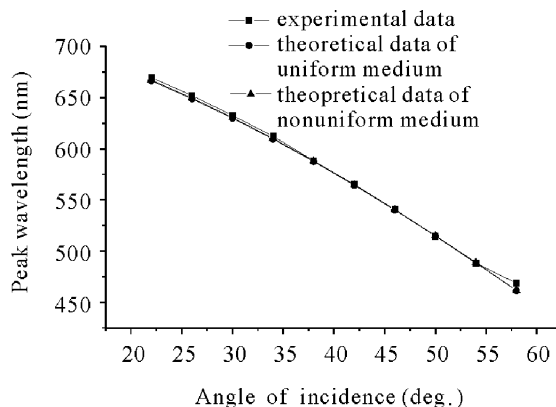


Fig. 6. Comparison of experimental and theoretical curves of $\lambda_f \sim \theta$.

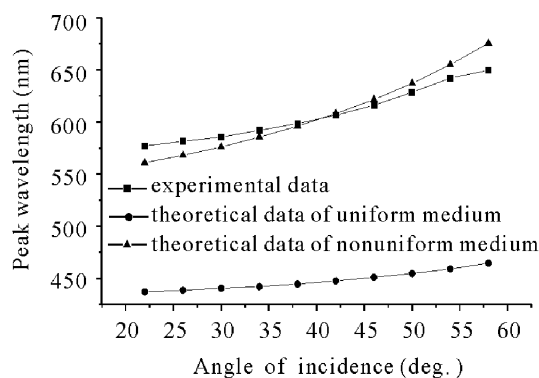


Fig. 7. Comparison of experimental and theoretical curves of $\Delta\lambda \sim \theta$.

results. The rationality of the coupled wave theoretical model for nonuniform medium is proved through analysis of the results and comparison with experimental results.

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