spectrometers are usually bulky and costly. Various efforts have been made to address this issue. As a well-known example, concave gratings [2] integrate the functions of the collimating and collecting curved mirrors as well as the diffraction grating in one device. A volume holographic spectrometer [3] has also been recently investigated, which can eliminate the entrance slit, collimating and collecting curved mirrors, as well as the grating all together with a volume hologram.

Here we explore planar diffractive optical elements that integrate the functions of lenses (or concave mirrors) and diffraction gratings. In particular, a G-Fresnel (i.e., Grating + Fresnel) device has been demonstrated by using polydimethylsiloxane (PDMS) soft lithography [4–6,10] which fuses the functions of a grating and a Fresnel lens into one hybrid device. Compared with existing devices, the G-Fresnel has two major advantages. First, it can have a smaller f/# (or large numerical aperture) compared with a conventional concave grating, and can therefore potentially result in a more compact spectrometer without significantly sacrificing the resolution. Second, the device has planar surface structures and hence can potentially allow for low-cost mass production by replicating from a master pattern.

2. Principle

In order to possess the dual properties of a lens and a grating, the desired field transmission (or reflection) coefficient of a diffractive optical element may be given by

$$t(x,y) \propto \eta(\lambda) e^{-j\frac{\pi}{\lambda F}\left(x^2+y^2\right)} e^{j\frac{2\pi}{\Lambda}x} \tag{1}$$

where λ is the wavelength, F is the focal length at λ, Λ is the grating period, and η represents the diffraction efficiency of the device. Since Eq. (1) comprises the product of the transmittances of a Fresnel lens and a linear grating, the diffractive optical element is referred to as G-Fresnel in the following. Let us consider a point source located at (x_0, y_0, -d) (c.f., Fig. 1). Under the paraxial approximation, the field distribution after the G-Fresnel can be obtained by applying the Fresnel diffraction formula [7] and is given by

$$\begin{aligned} f(x,y,z) &\propto \iint e^{j\frac{\pi}{\lambda d}\left[(x'-x_0)^2+(y'-y_0)^2\right]} p(x',y') e^{-j\frac{\pi}{\lambda F}\left(x'^2+y'^2\right)} e^{j\frac{2\pi}{\Lambda}x'} e^{j\frac{\pi}{\lambda z}\left[(x-x')^2+(y-y')^2\right]} dx'dy' \\ &\propto \iint e^{j\frac{\pi}{\lambda}\left(\frac{1}{d}-\frac{1}{F}+\frac{1}{z}\right)\left(x'^2+y'^2\right)} p(x',y') e^{-j2\pi\left[\left(\frac{x_0}{\lambda d}-\frac{1}{\Lambda}+\frac{x}{\lambda z}\right)x'+\left(\frac{y_0}{\lambda d}+\frac{y}{\lambda z}\right)y'\right]} dx'dy' \end{aligned} \tag{2}$$

where p(x, y) is the pupil function of the G-Fresnel. It can be shown that the geometrical image of the point source is located at (x_i, y_i, L), where

$$x_i = -\frac{L}{d}x_0 + L\frac{\lambda}{\Lambda},\ y_i = -\frac{L}{d}y_0,\ L = \frac{Fd}{d-F} = \frac{d}{\lambda d/\lambda_0 F_0 - 1} \tag{3}$$

and λ_0 and F_0 are the design wavelength and design focus length of the G-Fresnel respectively (note: $\lambda F = \lambda_0 F_0$ [8,9]). Therefore, a G-Fresnel can both image a point source (i.e., lens property) and disperse its different wavelength components (i.e., grating property). It can be shown from Eq. (3) that a linear relationship holds between x_i and L, i.e.,

$$L = \frac{\Lambda d}{\lambda_0 F_0 - x_0\Lambda} x_i - \frac{\lambda_0 F_0 d}{\lambda_0 F_0 - x_0 \Lambda} \tag{4}$$

In other words, the foci of the different wavelengths lie on a line with a slope dL/dx_i given by $\frac{\Lambda d}{\lambda_0 F_0 - x_0\Lambda}$.

Note that Eq. (1) can be rewritten as

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$$t(x,y) \propto \eta(\lambda) e^{j\frac{\pi}{\lambda F}x_c^2} e^{-j\frac{\pi}{\lambda F}\left[(x-x_c)^2+y^2\right]} \tag{5}$$

where $x_c = \lambda F / \Lambda$. In other words, a G-Fresnel is equivalent to an off-axis Fresnel lens with its center shifted to (x_c, 0). However, since the circular grating of a Fresnel lens is chirped and its period is inversely proportional to the distance from the center, such off-axis Fresnel lens becomes increasingly challenging to fabricate for large x_c. For instance, consider a grating period $\Lambda \sim \lambda$. The effective center shift is given by $x_c \sim F$, which would require a large Fresnel lens with sub-wavelength features.

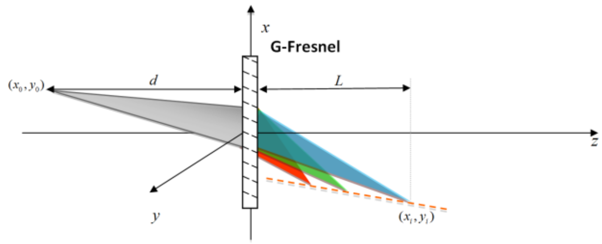

Fig. 1. Schematic diagram illustrating the dual focusing and dispersing properties of a transmission-type G-Fresnel.

The G-Fresnel can also be interpreted as a thin hologram. As shown in Fig. 2, let us consider a thin hologram recorded by a diverging spherical reference wave ($e^{j\frac{\pi}{\lambda l}\left(x^2+y^2\right)}$) and a converging signal wave ($e^{-j\frac{\pi}{\lambda l}\left[\left(x-\Delta x\right)^2+y^2\right]}$), where l is the distance between each point source and the recording medium and Δx is the relative displacement (along the x axis) between the two point sources. The transmittance (t_H) of the hologram is given by

$$\begin{aligned} t_H &\propto \left| e^{j\frac{\pi}{\lambda l}\left(x^2+y^2\right)} + e^{-j\frac{\pi}{\lambda l}\left[(x-\Delta x)^2+y^2\right]} \right|^2 = 2 + \left\{ e^{-j\frac{\pi}{\lambda l}\left(x^2+y^2\right)} e^{-j\frac{\pi}{\lambda l}\left[(x-\Delta x)^2+y^2\right]} + c.c. \right\} \\ &= 2 + \left[e^{-j\frac{\pi}{\lambda l}\Delta x^2} e^{-j\frac{2\pi}{\lambda l}\left(x^2+y^2\right)} e^{j\frac{2\pi}{\lambda l/\Delta x}x} + c.c. \right] \end{aligned} \tag{6}$$

The first term in the bracket of Eq. (6) (second line) is essentially a G-Fresnel if we identify $F = l/2$ and $\Lambda = \lambda l/\Delta x$.

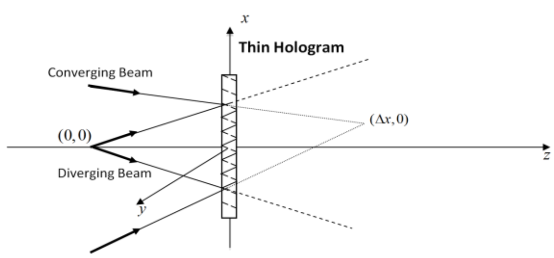

Fig. 2. Schematic diagram showing a thin hologram recorded with diverging and converging spherical waves.

3. Device fabrication and characterization

The G-Fresnel can be fabricated holographically as illustrated by Fig. 2. However, a thin hologram also contains a conjugate term (c.f. Eq. (6) and usually has limited diffraction efficiency. Here we describe a simple method to fabricate the G-Fresnel by using PDMS soft

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lithography [10]. The fabrication procedure is illustrated in Fig. 3. Briefly, PDMS pre-polymer mix (Dow Corning, Sylgard-184 PDMS, base to curing agent weight ratio 10:1) is poured onto the surface of a Fresnel lens (c.f. Figure 3a). After it is *in situ* cured at room temperature for two days, a negative Fresnel lens mold is formed and can be peeled off (c.f. Fig. 3b). Figure 3(f) shows a negative Fresnel mold fabricated this way. We then sandwich the PDMS pre-polymer between the negative Fresnel mold and a grating (Newport, 300lines/mm) (c.f. Fig. 3c). The grating is mounted on a linear translational stage, which can be used to adjust the distance between the two molds and hence the device thickness. After curing it for about two days at room temperature, a transmission-type G-Fresnel is fabricated (c.f. Fig. 3d). A photo of a transmission-type G-Fresnel fabricated by using such method is shown in Fig. 3(g). A reflection-type G-Fresnel can be readily obtained by coating the grating side of a transmission-type G-Fresnel with a thin layer of reflective film as illustrated in Fig. 3(e). Figure 3(h) shows a photo of reflection-type G-Fresnel, of which the grating side was coated with a layer of 50-nm-thick Au film by using a sputtering system (Kurt Lesker CMS-18/RF).

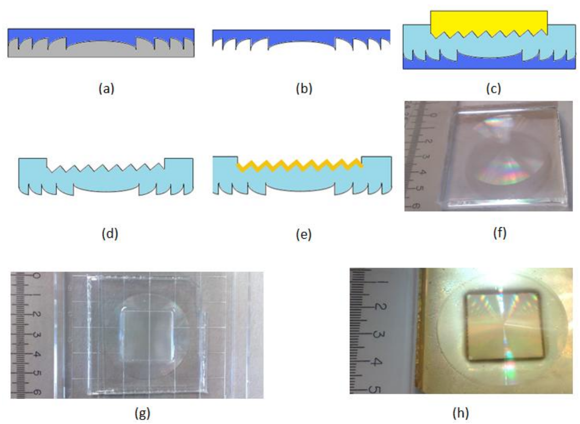

Fig. 3. Schematic diagram illustrating the procedure of fabricating a G-Fresnel; (a): PDMS pre-polymer mix is poured onto the surface of a Fresnel lens; (b): after it is *in situ* cured, a negative Fresnel lens mold is formed and can be peeled off; (c) PDMS pre-polymer is sandwiched between the negative Fresnel mold and a grating; (d): after curing a transmission-type G-Fresnel is fabricated; (e): a reflection-type G-Fresnel can be readily obtained by coating the grating side of a transmission-type G-Fresnel with a thin layer of reflective film; (f): a photo of a fabricated negative Fresnel mold; (g): a photo of a fabricated transmission-type G-Fresnel (h): a photo of a fabricated reflection-type G-Fresnel (Fresnel surface on top).

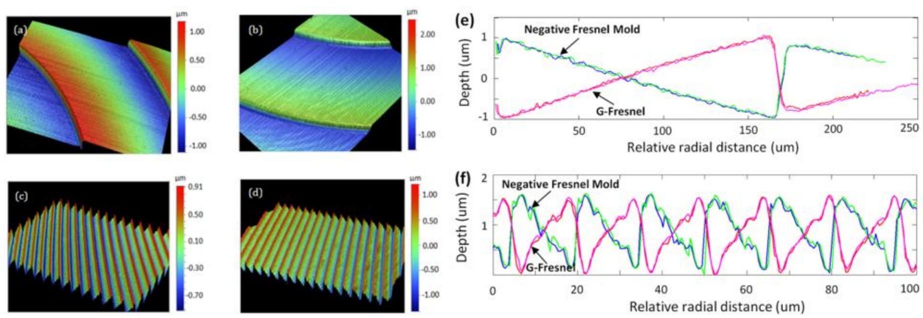

Fig. 4. Typical surface profiles of a negative Fresnel mold and the Fresnel side of a G-Fresnel measured by optical profilometry. (a) and (b): 3D surface profile near the central parts of a negative Fresnel mold and the Fresnel side of a G-Fresnel respectively; (c) and (d): 3D surface profiles near the peripheral parts of the negative mold and the G-Fresnel respectively; (e) comparison of surface height profiles along the radial direction near the central parts of the mold and the G-Fresnel; (f) comparison of surface height profiles along the radial direction near the peripheral parts of the mold and the G-Fresnel.

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In order to examine the quality of the fabricated G-Fresnel devices, we utilized a profilometer (WYKO NT1100) to measure the three-dimensional (3D) surface profiles of a negative Fresnel mold as well as the Fresnel side of a fabricated G-Fresnel. The results are given in Fig. 4, in which (a) and (b) show the typical 3D surface profiles near the central parts of the negative mold and the Fresnel side (of the G-Fresnel) respectively while (c) and (d) show those near the periphery. Figures 4(e) and 4(f) further show the typical surface height profiles along the radial direction near the central and peripheral parts of both devices. For the purpose of comparison, these plots are shifted by arbitrary amounts in order to align with each other. As expected, the height profiles of the negative Fresnel mold and the G-Fresnel (Fresnel side) exhibit anti-correlation. Clearly, good-fidelity pattern transfer from the mold to the G-Fresnel is achieved.

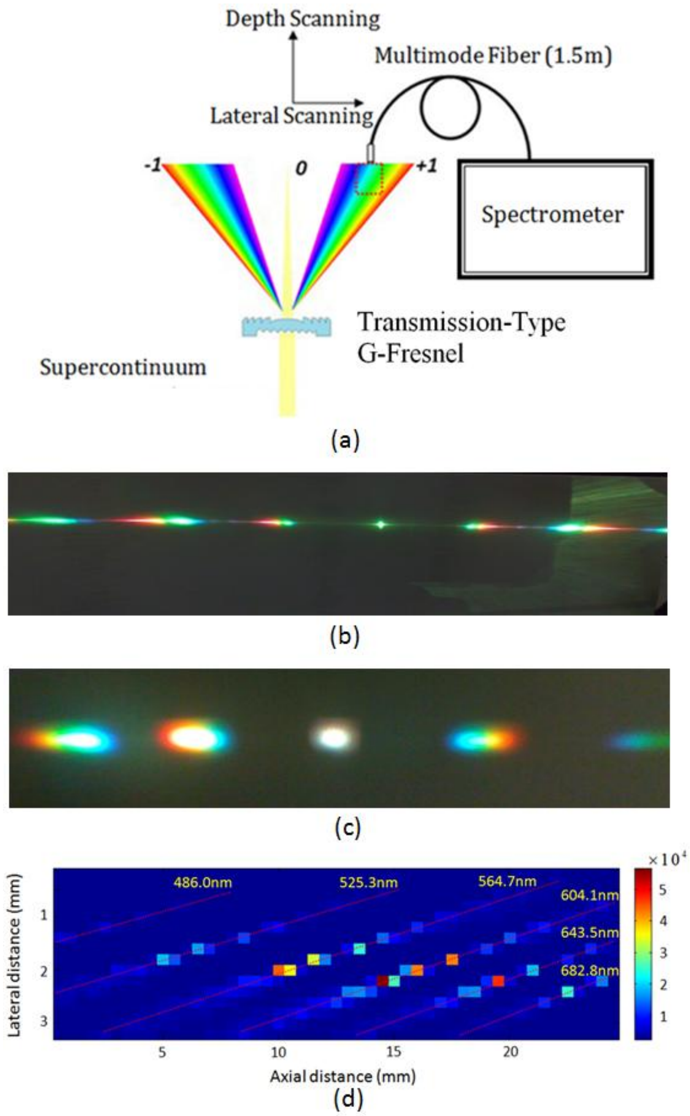

Fig. 5. Optical characterization results; (a) schematic diagram of the experimental system; (b) a photo of a focused diffraction pattern produced by passing a collimated supercontinuum through a transmission-type G-Fresnel; (c) diffraction pattern produced by a grating; (d) measured intensity distribution of several exemplary wavelengths (486.0 nm, 525.3 nm, 564.7 nm, 604.1 nm, 643.5 nm, 682.8 nm).

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We have also performed optical characterization of a transmission-type G-Fresnel (shown in Fig. 3g) by utilizing white light supercontinuum [11] generated by femtosecond laser pulses in a highly nonlinear photonic crystal fiber [12]. Figure 5(a) illustrates the schematic diagram of the experimental system. Briefly, a collimated supercontinuum beam (diameter: ~10 mm) was incident on the transmission-type G-Fresnel. The transmitted beam became focused and consisted of several diffraction orders as shown in Fig. 5(b). The central focused bright spot corresponds to the zero's order, i.e., directly transmitted beam, while the rainbows on both sides correspond to higher diffraction orders (± 1, ± 2…, etc). On the contrary, if the collimated supercontinuum is directly incident on a planar grating, only unfocused diffraction pattern can be produced as shown in Fig. 5(c). To further study this dual focusing and dispersion properties, we utilized a multimode optical fiber as a probe, which was placed behind the transmission-type G-Fresnel and scanned in two dimensions (i.e., along the axial and one lateral directions as illustrated in Fig. 5a) by using motorized translational stages. The scanning covered an area of 4 mm (lateral) x 25 mm (axial). The output of the multimode fiber was detected by a spectrometer (PI/Acton SpectraPro 2500 with a liquid nitrogen cooled charge coupled device detector PI/Acton Spec-10). Figure 5(d) presents the measured intensity distribution of several wavelength components. It shows that different wavelengths were focused by the transmission-type G-Fresnel and that they propagated along different directions. Our results clearly demonstrate that the G-Fresnel has the dual properties of a grating and a Fresnel lens, and can therefore both disperse and focus light. Note that according to Eq. (4) the foci trace of the different wavelengths is parallel the optical axis (z), as a collimated supercontinuum was used ($d \rightarrow \infty$). This is in agreement with the measured result shown in Fig. 5(d).

4. Conclusion

In summary, we have demonstrated a G-Fresnel device, which has the dual functionalities of a grating and a Fresnel lens. We showed in theoretical analysis that the G-Fresnel can both image a point source and disperse its various wavelength components. Double-sided transmission and reflection type G-Fresnel devices were fabricated by using PDMS based soft lithography. We also performed 3D surface profilometric measurements to evaluate the quality of the fabricated devices. Finally, optical characterization was performed to experimentally verify the dual focusing and dispersing properties of this device. With its potential for mass production through surface pattern replication and the possibility of achieving small f/#, the G-Fresnel can open a promising avenue for developing cost-effective, compact, and portable optical spectrometers. In addition, considering that it can be easily integrated with the optofluidic devices fabricated by PDMS soft lithography, we believe that the G-Fresnel can also find exciting applications in the emerging field of optofluidics [13] such as on-chip spectroscopy.

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