OPTICAL REVIEW Vol. 21, No. 5 (2014) 516–521

Design of Free-Space Optical Interconnects Using Two Gabor Superlenses

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(Received May 16, 2013; Accepted June 2, 2014)

We propose a novel design of micro-optical devices based on multi-aperture compound insect eyes, which transfer a point-to-point multichannel free space signal combined with a diffraction grating. The system is inspired in the refractive superposition compound eyes configuration known as Gabor superlens (GSL) using microlens arrays. A switching function and wave division multiplexing are achieved by introducing a diffraction grating placed in the global focus of the system. The source characteristics, either coherent or incoherent, influence the device performance.

Keywords: free-space optical interconnects, multiplexer, demultiplexer, compound eyes, multi-aperture optics, wave division multiplexing, Gabor superlens

1. Introduction

Optical communication systems (OCs) operate at a frequency of 100 THz, and the potential at bit rate of these systems is about 1 Tb/s. The function of a communication channel is to transport an optical signal from a transmitter to a receiver without distorting it. There are two main ways of transporting optical signals: in guided and unguided OCs. In guided lightwave systems, the optical signal remains spatially confined in order to reduce power loss. In unguided systems, the optical beam emitted by the transmitter spreads in free space. Their main advantage is that the signal processing is done at high speed and it allows the system to become more compact and reduce its dimensions.[1)] There have been attempts to design free-space modulators, multi-processors, and multiplexors.[2–4)] The common features of these designs include microlens arrays and diffractive elements.

In this work, designs of free space optical interconnects based on multi-aperture compound insect eyes that have two Gabor superlenses (GSLs) are presented. We propose an optical model that uses a set of microlens arrays in a GSL arrangement that combines multiple signals into one channel (multiplexation) and in an inverted GSL arrangement that separates the optical signal so that it will follow different paths (demultiplexation). We call this pair of GSLs a double GSL (DGSL).

The simulations of the DGSL were performed with and without a diffraction grating. The advantages and disadvantages of both designs are shown. The two cases are also used with two different kinds of sources: coherent and incoherent light. The DGSL design with coherent light and a diffraction grating achieves only optical switching, and the DGSL design with the incoherent source and the grating performs both optical switching and wave division multiplexing (WDM). Thanks to the current technology, the implementation of these designs in MOEMS fabrication may be possible. The result would be more compact unguided devices with acceptable quality and versatility. DGSL optical parameters, ray tracing, simulations, and the optical performance of the signal after propagating through the multiplexer/demultiplexer devices are shown.

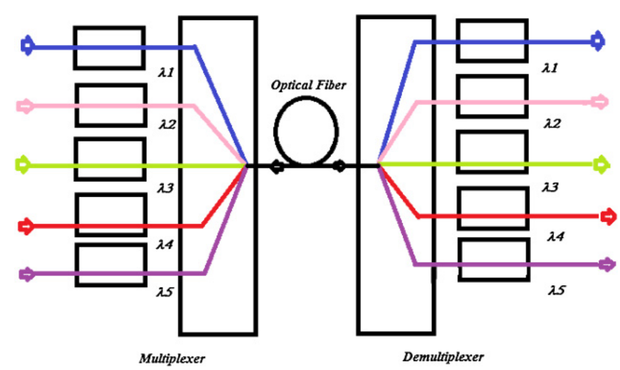

Fig. 1. (Color online) Multichannel point-to-point optical interconnects system with an optical fiber.[6)] Five different channels with different wavelengths (λ_1, λ_2, λ_3, λ_4, and λ_5) are multiplexed by a guided OCS and afterwards, they are demultiplexed to recover the original signals.

2. Optical Interconnects

One of the main categories of OCs are the point-to-point links. These systems work by multiplexing together the output of several transmitters, each operating at its own carrier frequency (or wavelength). The multiplexed signal is launched into the optical fiber for transmission to the other end, where a demultiplexer routes each channel to its own receiver.[3–5)] In Fig. 1, a conventional guided point-to-point interconnects system is shown. Signals from different channels with different wavelengths are mixed in a guided multiplexer, and they propagate in a single common channel that includes an optical fiber. The signals are recovered and separated into different wavelengths when they reach the demultiplexer.

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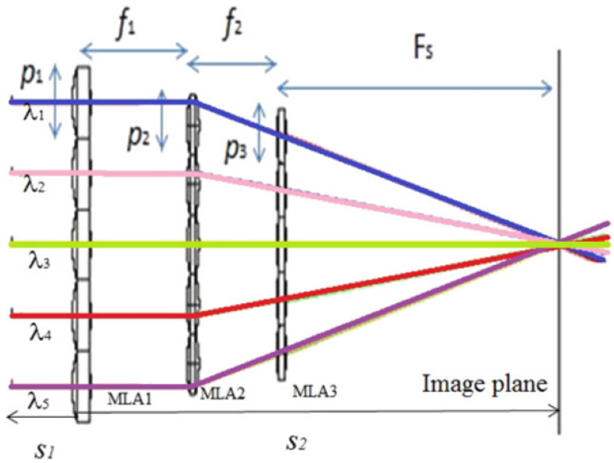


Fig. 2. (Color online) Configuration of GSL. Five different individual channels have different wavelengths (λ_1, λ_2, λ_3, λ_4, and λ_5). The pitches and focal lengths are shown for each microlens array.

A useful technique applied in optical communications is wave division multiplexing (WDM), in which two or more optical signals having different wavelengths may be simultaneously transmitted in the same direction through an optical fiber, and then separated by wavelength at the distant end.[7]

We tried to apply the natural principles of compound insect eyes to develop systems of optical interconnects. Compound eyes consist of multiple off-axis optical elements in comparison with single-aperture eyes. In superposition compound eyes (SCE), the refractive elements operate together to form an erect single deep-lying image. This kind of optical system is composed of arrays of micro-telescopes that form a combination of multiple units called *ommatidias*, which are placed one next to the other, to achieve a wider field of view. Thus, the different images formed by the multiple channels will superimpose at the image plane.[8,9]

Dennis Gabor patented an optical lens system based on refractive superposition compound eyes in order to achieve a special image formation.[10,11] Figure 2 shows this optical lens system, which is referred to as a GSL.

In Fig. 2 a GSL configuration comprising microlens arrays is shown. Three microlens arrays (MLA1, MLA2, and MLA3) are used to focus the light bundles to one common point. MLA2 is located at the focal length of MLA1, and MLA2 is related to the focal length of MLA3, (f_1 and f_2, respectively). The array positions provide the same function as that of multiple off-axis Kepler telescopes. In this configuration, p_1 is the pitch of MLA1, p_2 is the pitch of MLA2, and p_3 is the pitch of MLA3. f_1 is the focal length of MLA1, f_2 is the focal length of MLA3, and F_s is the back focal length of the complete system.[12] MLA2 can be used as a relay array.

A GSL must fulfill the back focus (F_s) conditions.

a) For an object at infinity: All rays from the same object point superpose at a common point in the image plane:[11]

Table 1. Lens parameters of the Keplerian microtelescopes.

Surface number	Radius of curvature R (μm)	Lens thickness d (μm)	Refractive index n
L_1	162	30	1.56384
L_1	−650	190	1.00000
L_2	165	20	1.78472
L_2	−164	150	1.00000
L_3	386	15	1.95250
L_3	−242	120	1.00000

Table 2. Lens parameters of the inverted Keplerian microtelescopes.

Surface number	Radius of curvature R (μm)	Lens thickness d (μm)	Refractive index n
L_4	242	15	1.95250
L_4	−386	120	
L_5	164	20	1.78472
L_5	−165	150	
L_6	650	30	1.56384
L_6	−162	190	

$$\frac{1}{F_s} = \left(\frac{f_1}{f_2}\right)\left[\frac{1}{f_1 + s_1}\right] + \left(\frac{p_3}{p_1}\right)\left[\frac{1}{f_2 - s_2}\right], \tag{1}$$

where s_1 and s_2 are the object and image distances from MLA1, respectively.

b) For an object at a finite location: The back focal length F_s for a finite object distance can be calculated; the height of a ray in the image plane must be independent of the channel through which it passed:[11,12]

$$F_s = f_2 \frac{p_1}{p_1 + p_3}. \tag{2}$$

If we propagate independent optical signals through each microlens channel parallel to the optical axis of the GSL configuration, all the signals will combine at the first image plane in a common point. Thus, the GSL configuration can achieve multiplexation. Also, an inverted GSL arrangement that achieves demultiplexation should fulfill Eqs. (1) or (2) depending on the case.

In order to evaluate the system's performance, the output power of an optical fiber should be compared with the output power of the system.

3. Free Space Optical Interconnects

The first step towards the design of the GSL is to establish the basic parameters of the Keplerian microtelescopes that perform the function of "artificial ommatidias".[13] The Keplerian microtelescopes, achieved by first-order design, are composed of the three refractive elements shown in Table 1.

The lens parameters of the inverted Keplerian microtelescopes are shown in Table 2. The simulations and optimization of the microtelescopes were performed in the sequential mode of Zemax©.

Table 3. Parameters of the DGSL demultiplexer.

	MLA1	MLA2	MLA3	MLA4	MLA5	MLA6
f-number $F\#$	1.9	1.78	2	2	1.78	1.9
Microlens pitch p_i (μm)	100	84	76	76	84	100
Radius of curvature R_{1i} (μm)	162	165	386	242	164	650
Radius of curvature R_{2i} (μm)	−650	−164	−242	−386	−165	−162
Thickness d_i (μm)	30	20	15	15	20	30
Refractive index n_i	1.56384	1.78472	1.95250	1.95250	1.78472	1.56384
Focal length f (μm)	190	150	150	150	150	190
Back focal length F_s (μm)	—	—	460	460	—	—

$i = 1, 2, 3, 4, 5,$ and 6.

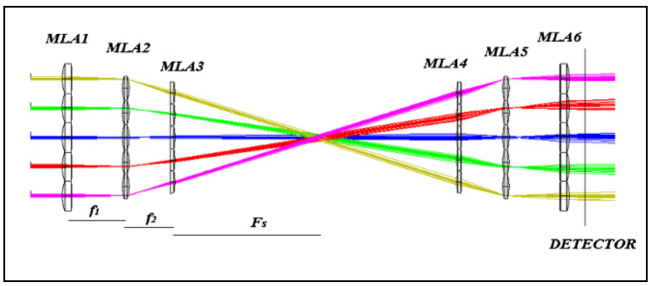
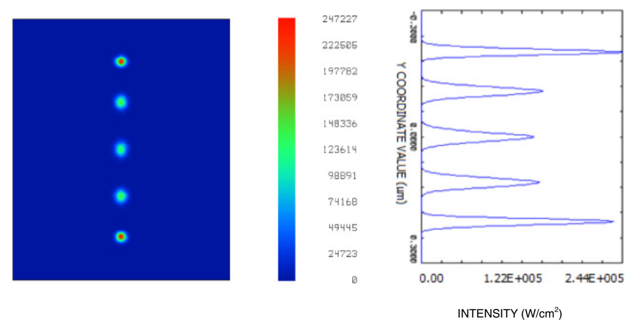


Fig. 3. (Color online) Configuration of the multiplexer/demultiplexer using a DGSL. Light comes from different sources and six microlens arrays are used.



(a) (b)

Fig. 4. (Color online) (a) Five recovered Gaussian beams, processed by a DGSL, captured at the detector plane. The spots appear wider because only part of the detector sees the intensity distribution better. The numerical description of the detector size is 0.60 mm wide and 0.60 mm high with 500×500 pixels. The pixel size is $1.2 \times 1.2\,\mu m^2$. (b) Incoherent irradiance profile of the five spots recovered in each channel. The intensity profile is measured in W/cm^2 for both figures.

The free-space interconnects were designed using Eqs. (1) and (2). The multiplexer/demultiplexer system consists of a DGSL configuration. L_1, L_2, L_3, L_4, L_5, and L_6 are the microlenses of each microlens array, MLA1, MLA2, MLA3, MLA4, MLA5, and MLA6, respectively.

In Fig. 3, a DGSL achieving multiplexing and demultiplexing is shown. After the multiple beams exit MLA3, all the beams are combined at the back focal point F_s. Thus, the multiplexer function is achieved. The inverted GSL composed of microlens arrays MLA4, MLA5, and ML6 divide the light beams and demultiplexes the optical signal.

The simulation of the DGSL was performed in the nonsequential mode of Zemax©. Four cases were considered:

a) DGSL with coherent sources,
b) DGSL with coherent sources and a diffraction grating,
c) DGSL with an incoherent source, and
d) DGSL with an incoherent source and a diffraction grating.

a) DGSL with coherent sources

The design parameters that represent the DGSL for coherent sources are shown in Table 3.

When many Gaussian beams of the same wavelength pass through the first three microlens-arrays of the GSL, a multiplexed signal is achieved. Afterwards, the signal propagates through the second GSL that divides the signal in multiple beams (see Fig. 3). It is very important to consider the size of the original Gaussian beam in comparison with the pitches of the microlenses. Better performance is achieved when the diameter of the beam does not expand considerably after the multiple refractions.

The diameter of the signal at the output of the demultiplexer may be larger than that of the input signal. This happens because of the behavior of the propagation of the Gaussian beams.

In the simulations, five Gaussian beams, parallel to the optical axis, each propagate along a different channel through a DGSL. Figure 4(a) shows the five spots of the five Gaussian beams captured at the image plane.

In the simulation, the intensity at the output of the demultiplexer is registered by the detector. Each signal is recovered in a different channel, and it is shown as an individual spot. In Fig. 4(b), the cross-column incoherent irradiance is also shown. The spatial distribution in the y coordinate is shown for each spot, and the units used to measure the irradiance are Watts/cm^2.

b) DGSL with coherent sources and a diffraction grating

The diffraction grating parameters used in the simulations are listed on Table 4. The grating equation for a transmission grating is[14)]

$$n_2 \sin\theta_2 = n_1 \sin\theta_1 + m\lambda/\Lambda, \qquad (3)$$

Table 4. Parameters of the transmission diffraction grating.

Material	BK7
Diameter (μm)	100
Thickness (μm)	10
Lines/micron	0.21
Diff. order	1

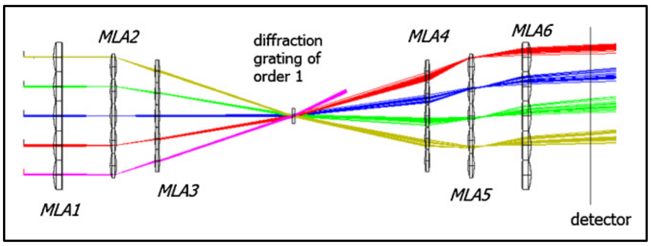


Fig. 5. (Color online) Double Gabor superlens demultiplexer processing Gaussian beams using a diffraction grating. A switching action is performed. The information recovered at the image plane is moved to the next upward optical channel.

where n_1 is the refractive index on the left of the grating and n_2 is the refractive index on the right, θ_1 is the incident angle and θ_2 is the exiting angle of the light leaving the grating, λ is the wavelength, Λ is the period of the grating, and m is the grating order.

We can see, in Fig. 5 a DGSL with a diffraction grating placed at the back focus F_s of the first GSL. If the grating operates with diffraction order 1, each channel is moved to the following upward channel to recover the image, whereas for diffraction order -1, the signals are moved downwards.

The proposed wavelength in the simulations for the coherent system is 1550 nm. We observe, as the result of the simulation of the propagation, a split in the diffraction orders (Fig. 6) owing to the presence of the diffraction grating.

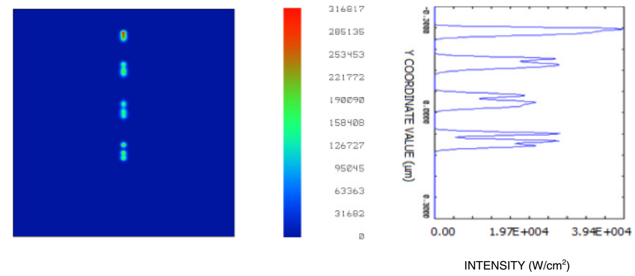
c) DGSL with incoherent source

Figure 7 shows white light being processed by a DGSL. The lens parameters in Table 5 were used to simulate the propagation for wavelengths between 440 and 680 nm. A plane wave from infinite, reaches the first GSL and the light is focused at F_s. The second GSL demultiplexes the focused optical signal.

The spots of the recovered optical signals in different channels are shown in the detector plane. In order to show a better view of the demultiplexing function, using the DGSL system with an incoherent source, the simulation was performed for the microlens arrays in a 2D matrix (Fig. 8).

d) DGSL with an incoherent source and a diffraction grating

Figure 9 shows white light being processed by a DGSL with a diffraction grating placed at F_s of the previous GSL. When a diffraction grating of order zero is introduced, the different wavelengths are slightly separated in the recovered signals.



(a) (b)

Fig. 6. (Color online) (a) Optical signal recovered by the detector in each individual channel. The DGSL system has a diffraction grating of order 1. The spots appear wider because only part of the detector better sees the different spots generated by the grating as well as the intensity distribution. The numerical description of the detector size is $0.60 \times 0.60\,\mathrm{mm}^2$, and 500×500 pixels. The pixel size is $1.2 \times 1.2\,\mu\mathrm{m}^2$. (b) Incoherent irradiance profile of the four recovered spots. The intensity profile is presented in $\mathrm{W/cm}^2$ in both figures. The information of the lower source is displaced upward owing to the switching by the DGSL system with the diffraction grating of order 1.

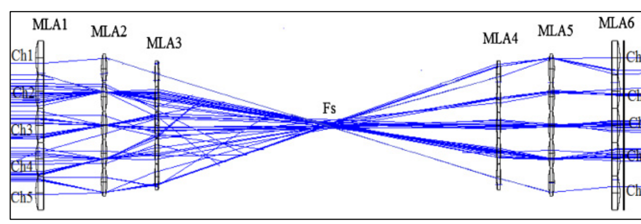


Fig. 7. (Color online) Ray tracing of the DGSL system with an incoherent source. The white light is collected by the microlenses of MLA1. The light signal coming from the source is referred as channels: Ch1, Ch2, Ch3, Ch4, and Ch5.

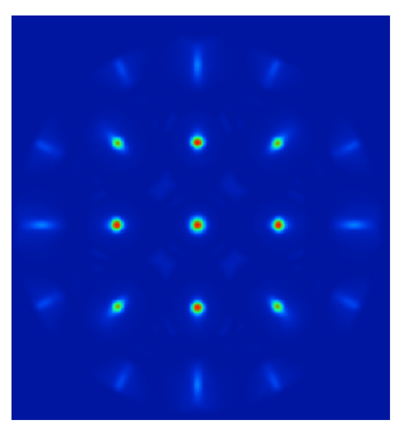


Fig. 8. (Color online) Demultiplexing performed by the DGSL system with an incoherent source. Each signal is recovered in an independent channel. The simulation was performed for the microlens arrays in a 2D matrix without a diffraction grating. The different wavelengths are still mixed up.

In Fig. 10, the recovered signals, processed by the DGSL in Fig. 9 at the image plane, are shown (diffraction grating of order 0 is used as above).

Table 5. Parameters of the demultiplexer used with an incoherent source with wavelengths between 440 and 680 nm.

	MLA1	MLA2	MLA3	MLA4	MLA5	MLA6
f-number $F\#$	2.3	2.26	2.5	2.5	2.26	2.3
Microlens pitch p_i (µm)	100	84	76	76	84	100
Radius of curvature R_{1i} (µm)	162	165	386	242	164	650
Radius of curvature R_{2i} (µm)	−650	−164	−242	−386	−165	−162
Lens thickness d_i (µm)	30	20	15	15	20	30
Refractive index n_i	1.56384	1.78472	1.95250	1.95250	1.78472	1.56384
Focal length f (µm)	230	190	190	190	190	230
Back focal length F_s (µm)	—	—	580	580	—	—

$i = 1, 2, 3, 4, 5,$ and 6.

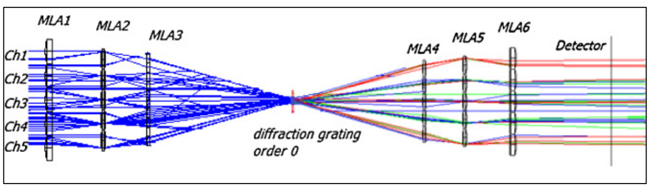


Fig. 9. (Color online) White light being processed by a DGSL with a diffraction grating of order 0 at F_s. The different wavelengths are separated to owing the diffraction grating.

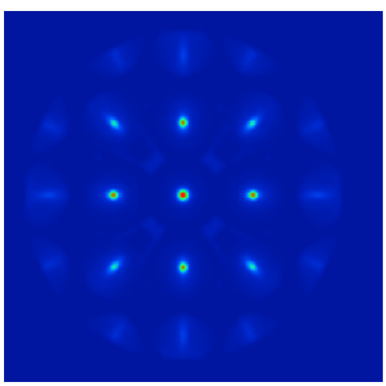


Fig. 10. (Color online) Demultiplexed optical signal by the DGSL in Fig. 9 (grating of order 0).

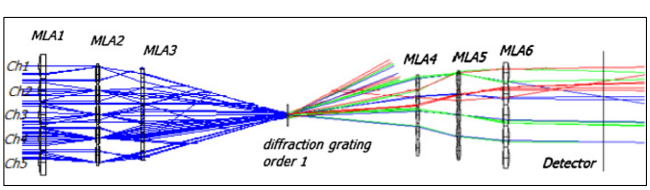
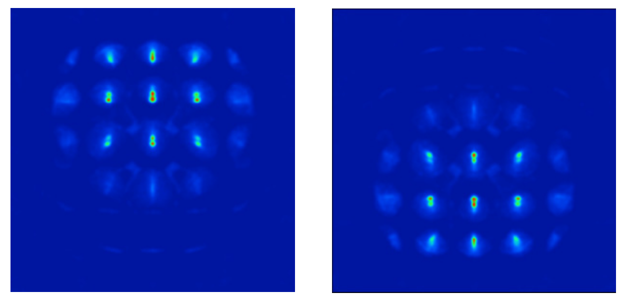


Fig. 11. (Color online) DGSL with an incoherent source and a diffraction grating of order 1. The different colors represent the different wavelengths divided by the diffraction grating of order 1. WDM is performed because the longer wavelengths tend to go to the lower channels and the shorter wavelengths to the upper channels of the demultiplexer. The grating displaces the exit signals one channel upwards.



(a) (b)

Fig. 12. (Color online) (a) Detected demultiplexed optical signal using a DGSL with a diffraction grating of order 1. (b) Detected demultiplexed signal with a grating of diffraction order −1.

Figure 11 shows switching and WDM functions performed by the DGSL optical system. The WDM function can be seen when the different wavelengths are diffracted by the grating and recovered by the correspondent optical channel by the inverted GSL. The blue and green colors can be found in the lower channels. Red mixed with other colors can be found in the upper channels. The wavelength separation can still be improved because the colors are not completely pure.

The switching function performed by the DGSL with diffraction gratings of order 1 and −1 are shown in Fig. 12. We can observe the displacement of the recovered spots in the detector plane for diffraction orders 1 and −1.

4. Conclusions

In this paper, we presented the performance of a GSL based on a multi-aperture refractive superposition compound eye. The proposed configuration enables either multiplexing (GSL) or demultiplexing (DGSL) of optical signals. The introduction of a diffraction grating enables the DGSL to function as an optical switch for coherent sources by changing the diffraction order of the grating. For incoherent sources, switching and wave division multiplexing (WDM) are achieved with the introduction of the grating. The GSL configuration has not been used before in the design of free-space interconnects. This model allows the application of the principle of compound eyes to optical communications with an acceptable recovery of the signal and versatility of the proposed devices.

Acknowledgments

We appreciate the financial support from CONACYT and INAOE for the current research project.

References

1) J. Kim, K. H. Jeong, and L. P. Lee: Opt. Lett. **30** (2005) 5.
2) M. Ménard, F. Thomas-Dupuis, and A. G. Kirk: Appl. Opt. **45** (2006) 122.
3) A. Kirk, D. Plant, T. Szymanski, Z. Vranesi, F. Tooley, D. Rolston, M. Ayliffe, F. Lacroix, B. Robertson, E. Bernier, and D. Brosseau: Appl. Opt. **42** (2003) 2465.
4) F. Thomas-Dupuis, M. Châteauneuf, and A. G. Kirk: Appl. Opt. **42** (2003) 5399.
5) T. Tamir: *Topics in Applied Physics, Integrated Optics* (Springer, Heidelberg, 1979).
6) A. Garza-Rivera, C. G. Treviño-Palacios, and F. J. Renero-Carrillo: Proc. SPIE **8428** (2012) 84281E.
7) G. P. Agrawal: *Fiber-Optic Communication Systems* (Wiley, New York, 1992).
8) M. F. Land: Nature **287** (1980) 681.
9) M. F. Land and D. E. Nilsson: *Animal Eyes* (Oxford University Press, Oxford, U.K., 2002).
10) D. Gabor: UK Patent 541 753 (1940).
11) C. Hembd-Sölner, R. F. Stevens, and M. C. Hutley: J. Opt. A **1** (1999) 94.
12) K. Stollberg, A. Brückner, J. Duparré, P. Dannberg, A. Bräuer, and A. Tünnermann: Opt. Express **17** (2009) 15747.
13) W. Smith: *Modern Optical Engineering* (McGraw-Hill, New York, 2010).
14) J. W. Goodman: *Introduction to Fourier Optics* (Robert & Co., Atlanta, GA, 2005) 3rd ed.