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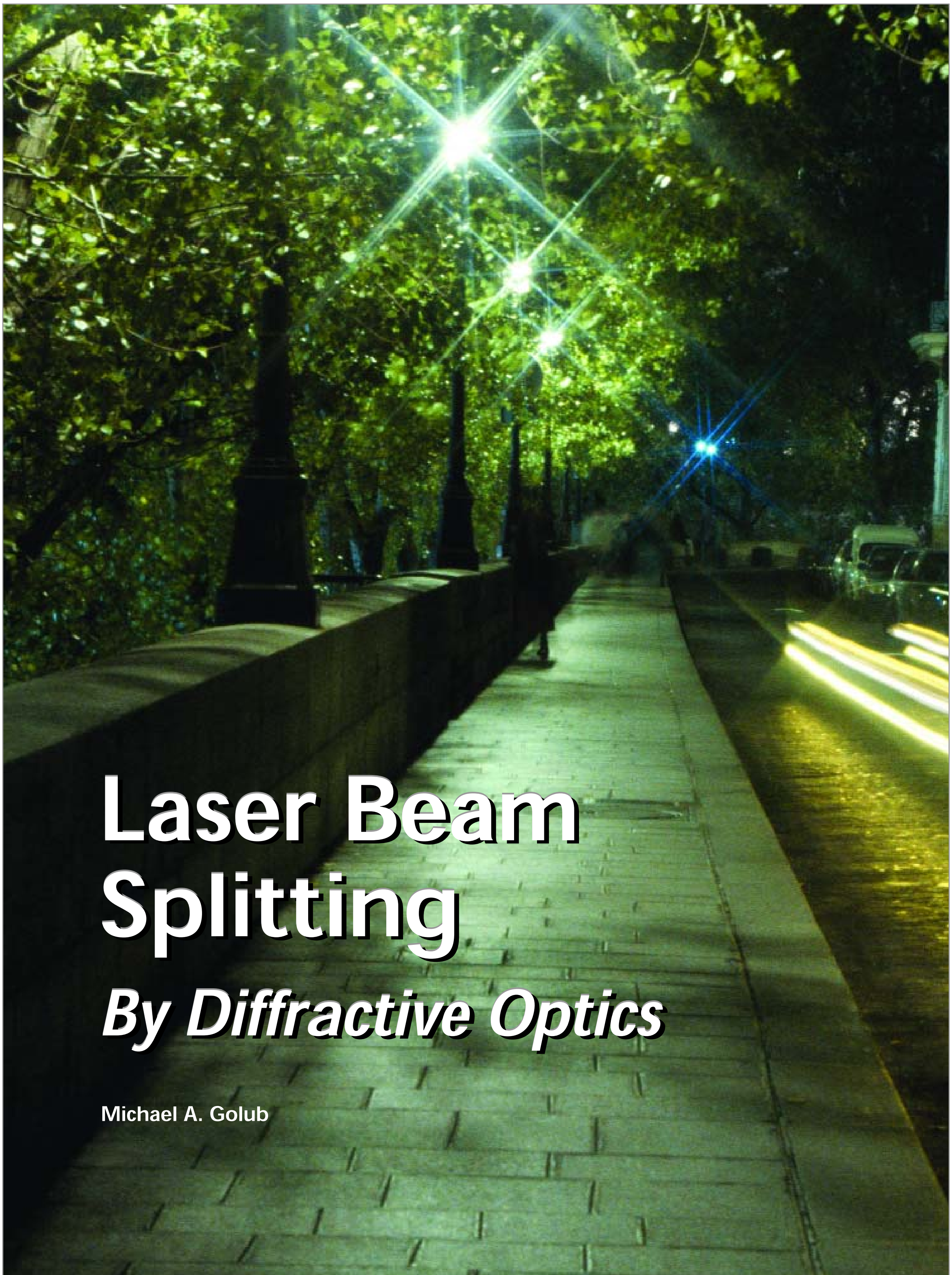

Laser Beam Splitting

By Diffractive Optics

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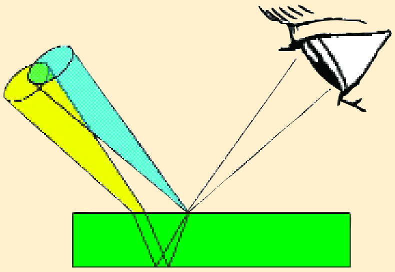

Recent advances in diffractive optics theory and technology have made beam splitting a valuable resource for optical designers. Programmable, multichannel optical systems can be designed based on diffraction gratings, lenslet arrays and digital holography algorithms. Spot array generation, multiple and multifocal imaging, matched filtering, laser beam mode selection and simultaneous contour shaping are among the most promising applications of diffractive beam splitting today.

Beam splitting, the creation of several beamlets from a single beam of light, is both a technology and an art. The beamlets created through beam splitting are usually exact copies of the incident beam and they bear part of its power. Some beamlets, however, have specific features, for example in terms of wavelength or spatial distribution.

In the natural world and in everyday life, beam splitting occurs all around us. Rainbows are a demonstration of spectral beam splitting. When we observe a street light through a curtain or other type of diffraction grating, we see a raster of points (Fig. 1). Another beam splitting effect, known since the time of Newton, occurs when two cones of light are observed by a human eye accommodated on the surface of a plane-parallel plate (Fig. 2). Most optics lab set-ups make use of a classical beam splitting cube, plate wedge or prism to create two copies of an incident beam. More complicated arrangements make use of several semi-transparent mirrors inserted in the path of the beam.

A number of modern technologies require splitting to as many as a few dozen beamlets. They include laser technology, microelectronics, microscopy, optical communications and optical image processing. The critical issues are high diffraction efficiency and uniform power distribution between beamlets. In this complex scenario, which goes far beyond classical and historical approaches to beam splitting, a number of equivalent terms for diffractive beam splitter exist. They include spot array generator, fan-out elements and multiple beam gratings.

Figure 1. (*Facing page*) Beam splitting in photograph taken through diffraction gratings.
Figure 2. (*Above*) Beam splitting by plane parallel plate. [Drawing adapted from E. Mach, *The Principles of Physical Optics, An Historical and Philosophical Treatment*, Dover Publications Inc., 1953.]

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Basic design concepts

Although beam splitting is easy to describe, it can be difficult to accomplish. Figures 3 and 4 illustrate two main variants of beam splitting. A diffraction grating type beam splitter will convert a single plane wave to a set of plane waves with progressive slopes (Fig. 3). In the same way, a spherical incident beam will be converted into a set of spherical beams, with different directions of propagation, which "rotate" around the center of the beam splitter. It is obvious that, to obtain several spherical beams from an incident plane wave, the focusing function of a regular lens could be used in combination with the grating type beam splitter (Fig. 4). Today, most design approaches are based either on lenslet arrays or on diffraction gratings.

The following parameters are used to describe the characteristics of beam splitters: clear aperture; wavelength; input beam diameter and divergence; number of beamlets; separation between beamlets; power distribution between beamlets (usually uniform); total diffraction efficiency (portion of incident beam power diffracted to required beamlets); uniformity of beamlets' power; and maximum power of side-lobe (ghost) beamlets. Generic designs usually assume the far-field output plane and a good degree of separation between beamlets. In practice, the designer must manage the relationship between the initial beam diameters, the natural widening of the beamlets as they propagate and the required separation of beamlets. Computer simulation is useful during the design process in estimating performance. Computer simulations of the data in the figures in this article were carried out with commercial diffractive optics software code DOE-CAD.[1]

A number of modern technologies require splitting to as many as a few dozen beamlets. They include laser technology, microelectronics, microscopy, optical communications and optical image processing.

A diffractive beam splitter is usually designed as a periodic structure and built from one-dimensional (1D) or 2D periods analogous to the "lenslets," or grooves, in the diffraction grating. The idea behind diffractive beam splitting is that diffraction effects yield several diffraction orders. The angles θ_m of diffraction are determined by the well-known grating equation:

$$\Lambda \sin\theta_m = m\lambda,$$

where λ is a wavelength, Λ is the period and m is the number of the diffraction order. Diffraction efficiency η_m is defined as the portion of incident beam power in a given m^{th} diffraction order. The total diffraction efficiency of a beam splitter is simply the sum of η_m with respect to the required diffraction orders. In the context in which scalar diffraction theory is applicable, there is a straightforward Fourier transform relation between the arbitrary groove shape $h(x)$ within period Λ, the groove refractive index n and the diffraction efficiency

$$\eta_m = \left| \frac{1}{\Lambda} \int_0^{\Lambda} \exp\left[i\frac{2\pi}{\lambda}(n-1)\,h(x) - im\frac{2\pi}{\Lambda}x \right] dx \right|^2;$$

this relation is the basis for scalar theory design of a diffractive beam splitter. The essence of beam splitter design is closely related to the general kinoform problem of digital holography: one must find the phase-only function $\sim h(x)$ which delivers the uniform squared modulus η_m (with arbitrary phase) of the Fourier transform. The special feature of a beam splitter is to be found in the periodic nature of phase function which results in discrete Fourier transform rather than in continuous Fourier transform. Depending on whether the number of beamlets is even or odd, specific symmetries—as described in the works of R. L. Morrison—should be used in design.[2]

A rigorous approach to diffractive theory (described in the works of J. Turunen, M. Kuittinen and F. Wyrowski,[3] E. Sidick, A. Knoesen and J. N. Mait[4] and other research groups), in contrast with scalar theory, gives more degrees of freedom in the design of beam splitters with high fan angles and improved uniformity of intensity distribution between beamlets.

Lenslet arrays

Most classical beam splitting design exploits lenslet arrays. Lenslet arrays are usually associated with several foci

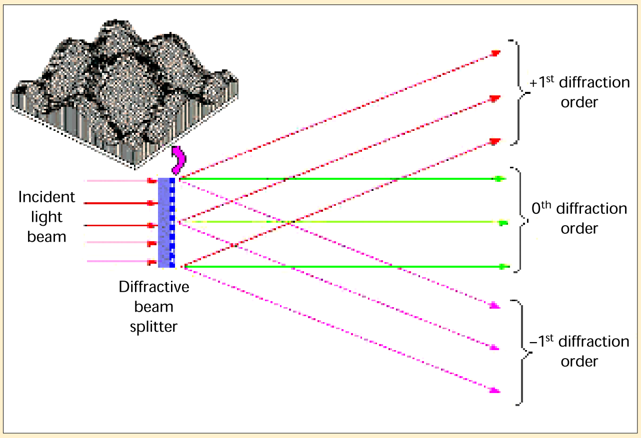
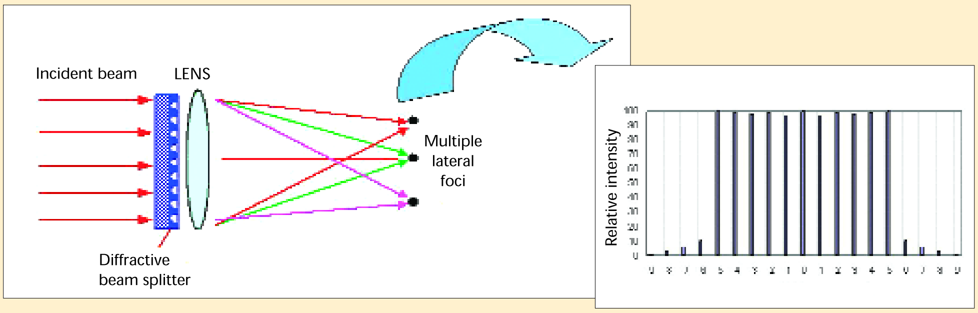


Figure 3. General principle of diffractive beam splitting.



formed at the focal plane; the spacing between foci corresponds to the size of the lenslet. Lenslet arrays may however be treated as beam "diffusers," with the fan-out cone angle directly related to the numerical aperture. In the far-field zone, we see superposition of similar diverging beams originating from the lenslets (when lenslet arrays are used). In coherent light, as predicted by diffraction grating theory, the superposition will result in a discrete structure of diffraction orders. The location of each diffraction order is determined by the dimension of each lenslet, while the intensity distribution between orders is defined by the phase profile of the lenslet. Incoherent illumination converts the beam splitter into a beam homogenizer.

The simplest spherical profile of a lenslet yields decreasing-to-periphery, far-field intensity distribution and consequently nonuniform powers of diffraction orders or beamlets. In some cases, the use of a conical section profile of the lenslet (as investigated by D. Shin and R. Magnusson[5]) or even of a higher order aspherical profile, may improve the situation as far as uniformity is concerned.

Rectangular profile gratings

Multiple order diffraction gratings are the most frequently used source of diffractive beam splitters. Rectangular profile diffraction gratings which have two phase levels, such as 0 or φ_0, are very popular for obtaining two or three beams. The diffraction efficiency of a symmetrical rectangular profile grating is determined from a simple equation:

$$\eta_m = \begin{cases} \cos^2[\varphi_0/2], m=0 \\ (2/\pi m)^2 \sin^2[\varphi_0/2], m=\pm1,\pm3,\ldots \\ 0,\ m=\pm2,\pm4,\ldots \end{cases}$$

where phase delay φ_0 on the groove is related to the depth of groove h_0 and its refractive index n as

$$\varphi_0 = \frac{2\pi}{\lambda}(n-1)\,h_0 .$$

On the basis of a design in which phase delay φ_0 is equal to π, the zero diffraction order is eliminated by interference and the +1 and –1 orders are the most powerful, with 40.5 percent of the incident power going to each of them. Higher orders still hold 19 percent of the power in this case. Total diffraction efficiency is 81 percent. In a design in which φ_0 is equal to about 0.64π, a rectangular groove grating is converted into a tribeam splitter with 29 percent of the power equally delivered to +1, 0 and –1 order and an overall diffraction efficiency of 87 percent.

Dammann gratings

Pioneering work by Dammann[6] gave rise to considerably more complicated gratings capable of splitting a beam into several dozen beamlets. Although the phase profile of the Dammann grating is still two-level with a phase delay of 0 or π, each period is quite complicated, consisting of several grooves created at special coordinates designed by unique algorithms. The drawback of the Dammann grating is relatively low efficiency, usually no higher than 65-80 percent for 1D spot arrays and 50-70 percent for 2D spot arrays. The demand for higher diffraction efficiency, at levels above 90 percent, brings us to grating grooves featuring multiple or even continuous levels of phase.

Multilevel diffractive optical elements

In a certain sense, the use of multilevel diffractive optical elements combines the principles underlying the Dammann grating on the one hand with the properties of lenslet arrays on the other. Research by D. S. Prongue, H. Herzig, R. Dandliker, MT. Gale[7] and others has shown that the profile of the more complicated "lenslet" should be non-monotonic and feature few additional peaks in addition to the main one. Compared with classical lenslet arrays, such a complicated periodic structure delivers much better uniformity and higher diffraction efficiency.

The phase profile in each period can be optimized by the choice of lenslet parameters and by computer simulation of the far-field diffraction pattern. Various numerical iterative algorithms[7-9] optimize the pixels of the phase profile in each 2D period—or lenslet—of the beam splitter by setting the deterministic and random initial phases of the beamlets. In practice, the algorithms are the "periodic version" of the general phase retrieval task resolved by iterative algorithms such as the Gerxberg-Saxton algorithm and more advanced simulated annealing generic optimization algorithms. An important problem is the interpolation of the optimized phase profile in the period of the optical element so as to meet the submicrometer resolution requirements of masks in beam splitter fabrication. A typical phase profile and a fragment of computer-simulated intensity are shown in Figs. 3 and 4.

A planar light-guide optic for beam splitting

As shown in the work of A. A. Friesem's group, beam splitting can also be achieved by use of a light guide with spatially variable diffraction efficiency surface relief diffraction gratings.[10] The advantage of this type of planar optics approach can be found in parallel as opposed to fan-out directions of beam propagation.

One challenge in making multifocal lenses is merging the lens and the beam splitting diffraction grating. Another is structuring the variable period of a diffractive lens so that it follows the shape of the groove of the beam splitting grating.

Applications

Diffractive beam splitters with uniform power distribution between beamlets find commercial applications in a number of fields, including: laser-based materials processing; mask generating and step-and-repeat devices in microelectronics; multiple imaging in optical information processing; laser radar; range finding; optical interconnects; fiber optics (Fig. 5); laser printing; confocal microscopy; Hartman tests; expression through filters in photography; multiple image and diffraction effect filters in photography; and multifocal and contact and intraocular lenses in ophthalmology. Another example is beam sampling, in which powerful zero diffraction order and weaker higher orders are required. More complicated applications, such as pattern recognition with multichannel matched optical filters, demand that beams be split into spatially modulated beamlets.

Multifocal lenses

One challenge in making multifocal lenses is merging the lens and the beam splitting diffraction grating (see Fig. 4). Another challenge is structuring the variable period of a diffractive lens so that it follows the shape of the groove of the beam splitting grating. The simplest example of a multifocal lens is a Fresnel binary zone phase plate. We can treat the phase profile of this plate by applying a hard clipping nonlinearity at each point of the continuous profile of the diffractive lens. When illuminated by the plane wave, the Fresnel zone plate gives rise to three main beams: collimated zero order; converging +1 order; and diverging –1 order (Fig. 6). On the basis of this principle, we can use the groove profile of each beam splitting grating as a kind of nonlinearity which can be applied to the continuous profile of the diffractive lens. This allows us to obtain a Dammann-type lens, a continuous profile beam splitting lens and so forth. Such multifocal lenses are impor-

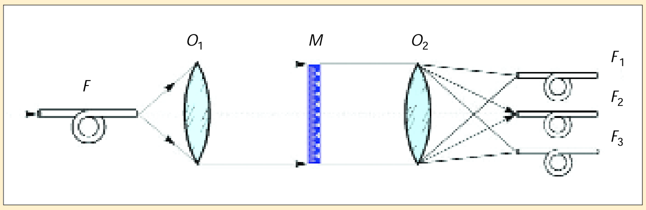


Figure 5. Coupling of fiber F with several fibers F_1, F_2, F_3. Beam splitting and mode selection are performed by diffractive optical element M. O_1, O_2 objectives. [From Fig. 3.9 in the book listed in Ref. 11.]

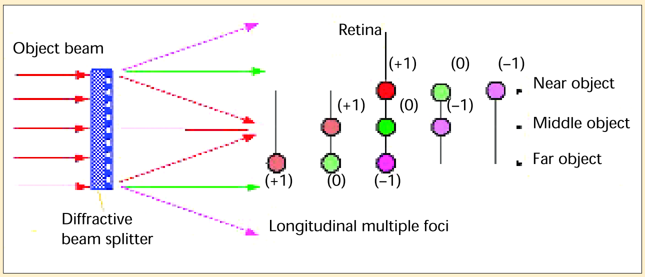


Figure 6. Multifocal diffractive lens for simultaneous vision.

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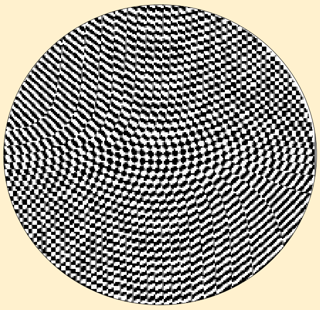

Figure 7. Mask of diffractive optical element for rectangular contour pattern generation; each line of contour is reproduced by 2 x 2 beam splitting merged with uniform "top-hat."

tant in ophthalmic applications, optical sensors and parallel zoom systems. Multifocal contact lenses, for example, compensate for the lack of accommodation in the presbyopic human eye by providing simultaneous vision of near, middle and far objects (see Fig. 6).

Multichannel optical elements

Classical beam splitting produces several beams that are identical except for direction of propagation. Matched filters and mode selection elements are examples of beam splitters with modulated output beams. One application is to couple (or split) the beam propagating inside a multimodal input fiber F into several output fibers so that each output fiber receives only single-mode power of a given lower or higher order. The design of such elements is quite complicated and requires superimposing all partial modal beams on the plane optical element and encoding multimodal complex amplitude to a phase-only function with the highest possible efficiency. This method follows the digital holography approach described in the book by V.A. Soifer and M.A. Golub.[11]

Contour shaping of the beam

Let's assume we need to transform a Gaussian beam into a contour-like focus such as a ring, a square line contour or a letter. Classical beam shaping would exploit either map transformation techniques or spot array generators. A better idea would be to construct the output beam contour from partial lines by diffractive splitting. I designed a diffractive element which builds the square line contour from four straight lines. Figure 7 depicts a mask of a two-phase-level–only diffractive element that performs with an efficiency of 81 percent.

Trends

Toward the end of 1989, there was intense debate over whether diffractive optics was a scientific field or an emerging industry comparable to microelectronics. Only a short time later, diffractive beam splitters and beam shapers have become commonplace on the market at large as well as in optics research labs

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References

1. Developed and distributed by Holo-Or Ltd., Israel.
2. R. L. Morrison, J. Opt. Soc. Am. A **9**, 464 (1992).
3. J. Turunen, et al., "Diffractive optics: an electromagnetic approach," In: *Progress in Optics*, E. Wolf, ed., **XL**, Elsevier Science B.V. (2000).
4. E. Sidick, et al., Appl. Opt., **32**, 2599 (1993).
5. D. Shin and R. Magnusson, J. Opt. Soc. Am. A **6**, 1249 (1989).
6. H. Dammann and M. Kock, Opt. Comm. **3**, 312 (1971).
7. D. S. Prongue, et al., Appl. Opt. **31**, 5706 (1992).
8. V. Arrizon, et al., J. Opt. Soc. Am. A **17**, 2157 (2000).
9. D. Mendlovic, et al., Appl. Opt., **35**, 6875 (1996).
10. R. Shechter, Y. Amitai and A. A. Friesem, Appl. Opt. **41**, 1236 (2002).
11. V.A. Soifer and M. A. Golub, *Laser Beam Mode Selection by Computer Generated Holograms*, CRC Press, Boca Raton (1994).

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