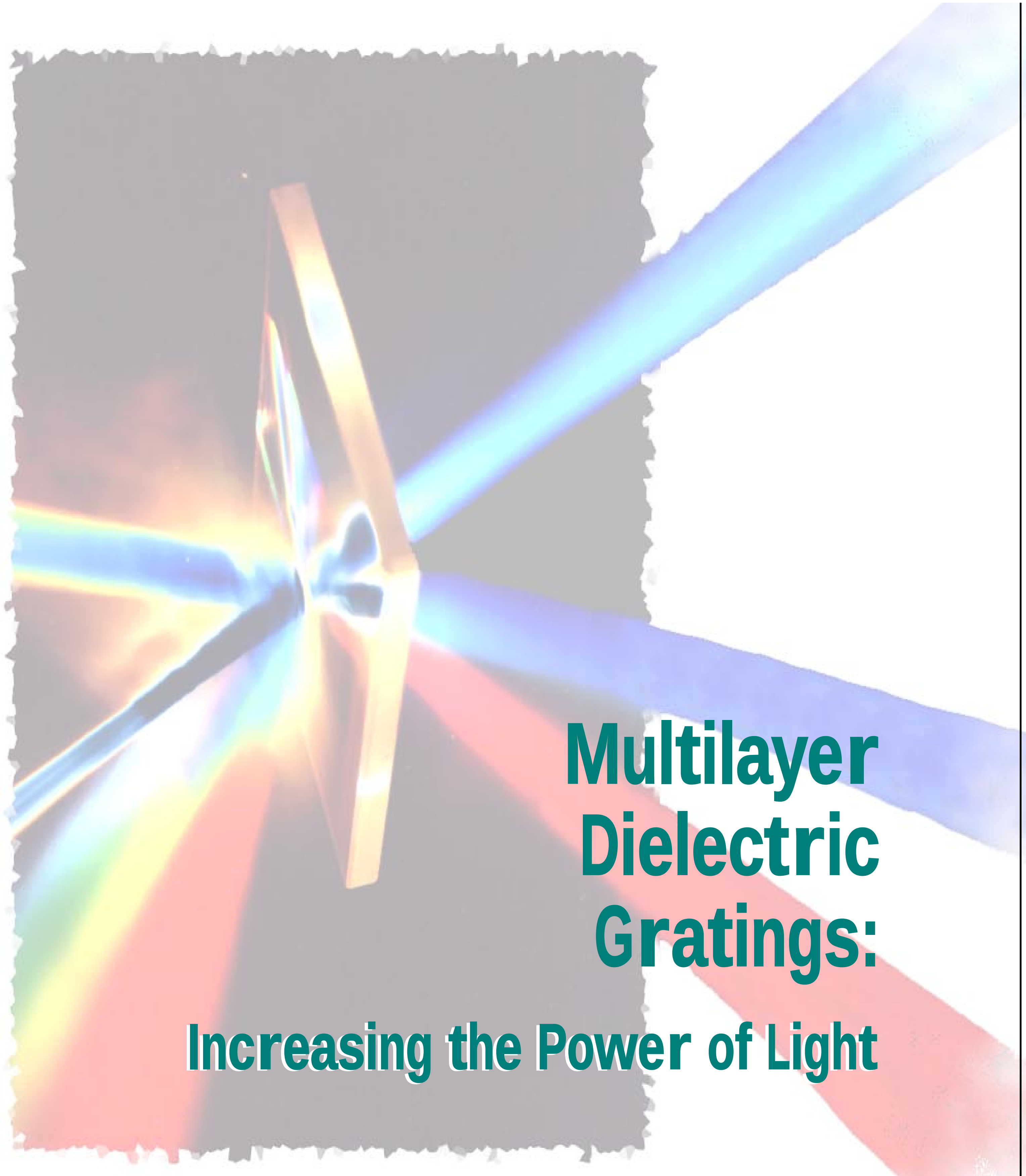

Multilayer Dielectric Gratings:

Increasing the Power of Light

Diffraction gratings are an essential component of high-power, short-pulse lasers. Novel grating designs using dielectric materials (insulators) rather than on traditional metallic (conducting) surfaces can significantly increase the output of high-power pulsed lasers. Their unique characteristics give these gratings numerous potential applications.

OVER the years, pulsed lasers, such as the Shiva and Nova lasers at Lawrence Livermore National Laboratory, have become ever more powerful. We have built laser systems that generate more than a trillion watts (a terawatt, or 10^{12} W) and will soon complete a quadrillion-watt (10^{15}-W) laser. The duration of these pulses is less than a trillionth of a second (a picosecond, or 10^{-12} s). At the Laboratory, we have completed construction of a short-pulse 100-terawatt (TW) laser, an important step toward a petawatt laser, which is scheduled for completion by the end of 1995.*

The development of short-pulse, high-power lasers is important in the continued progress of our inertial confinement fusion program. The fast ignitor concept, described on p. 36, would use high-power laser pulses to advance our fusion power efforts. We are also studying the propagation of strong shocks, such as those generated by high-power laser pulses, to provide information on the fundamental properties of matter (for example, the equation of state of a material). These investigations are particularly important for the Laboratory's science-based stockpile stewardship efforts. The technology of short-pulse lasers also has applications to materials processing, medicine, and dentistry.

Recent developments in solid-state laser materials and the use of chirped pulse amplification[1] (CPA) have dramatically increased the intensity available with pulsed lasers. To recognize the importance of this new technology, one must appreciate some of the constraints that have previously limited the output of pulsed lasers. A laser pulse gains electromagnetic energy by extracting energy stored (as atomic excitation) in an optical amplifier. Solid-state amplifier materials make it possible, in principle, to extract several joules of energy from laser systems of modest size. In certain laser materials, the energy is available over a broad bandwidth of frequencies, an important prerequisite for short pulses. However, as the intensity of the light grows, it induces changes in the optical response of the amplifier medium. The consequent alterations of the refractive index of the amplifier medium cause the laser beam to self-focus inside the laser system. This self-focusing can result in catastrophic damage to the laser. To avoid self-focusing, it is necessary to limit the intensity that is present in amplifiers of reasonable length to less than a few gigawatts per square centimeter (1 gigawatt = a billion watts, or 10^9 W).

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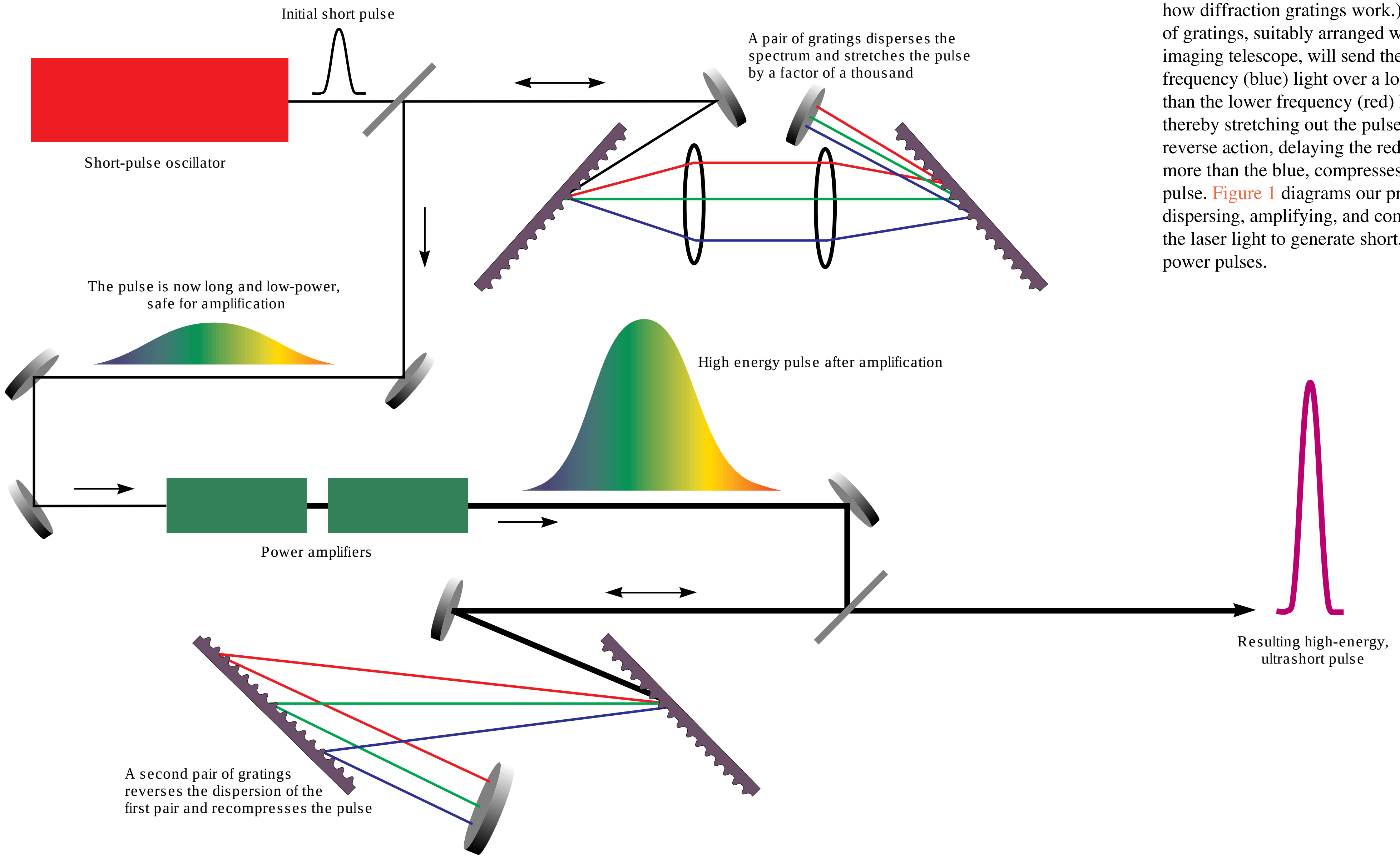
* For more information on the 100-TW laser, see the Research Highlight beginning on p. 34 of this issue.

Because the detrimental effects of self-focusing are proportional to instantaneous intensity rather than to accumulated pulse energy (fluence), it is possible to overcome this obstacle by amplifying a long-duration pulse and then compressing the pulse to the desired duration. Briefly stated, we first generate a broad-bandwidth seed pulse, typically 100 femtoseconds in duration (1 fs = 10^{-15} s). We then stretch the duration of this pulse by a factor of ten thousand or more, pass it through amplifiers where it grows in energy by as much as a trillion, and compress it back into a short pulse of extremely high intensity.

The first step is to produce the broad-bandwidth pulse and to impose on it a controlled frequency sweep or "chirp," in which the different frequencies occur at different times. The bandwidth of the pulse is critical to the chirped pulse amplification technique because pulse stretching or compression relies on manipulating the various frequencies or "colors" contained within the pulse. Any device that delays certain frequencies relative to others could stretch a short pulse over a longer time or, alternatively, compress a long broad-bandwidth pulse into a short one. We use diffraction gratings for this purpose, sending light rays of different frequencies in different directions. (The box on p. 28 describes how diffraction gratings work.) A pair of gratings, suitably arranged with an imaging telescope, will send the higher frequency (blue) light over a longer path than the lower frequency (red) light, thereby stretching out the pulse. The reverse action, delaying the red light more than the blue, compresses the pulse. Figure 1 diagrams our process of dispersing, amplifying, and compressing the laser light to generate short, high-power pulses.

Figure 1. Schematic of beam stretching, amplifying, and compressing system used to give different beams longer or shorter paths.



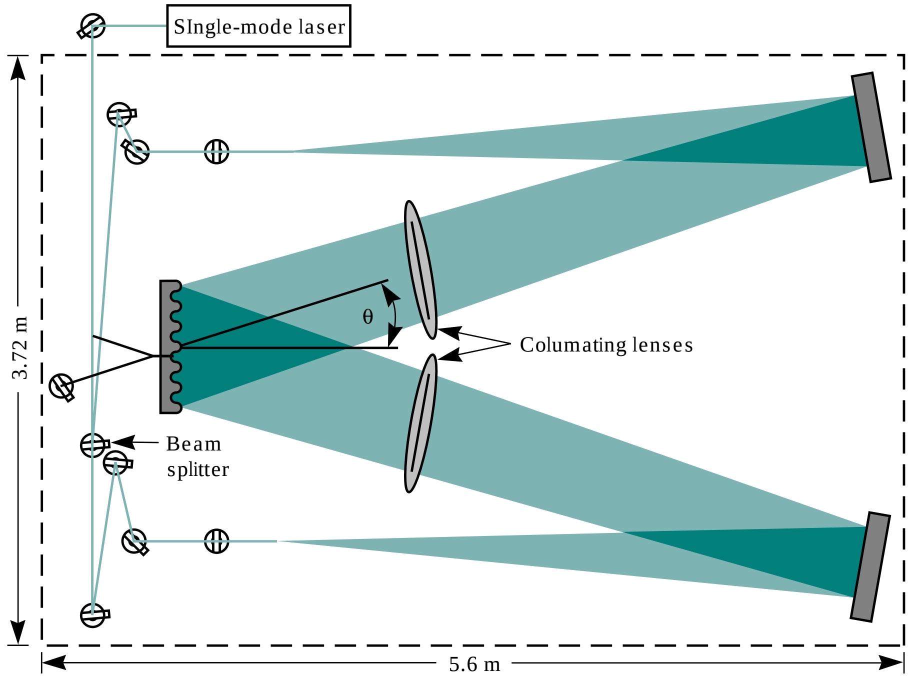


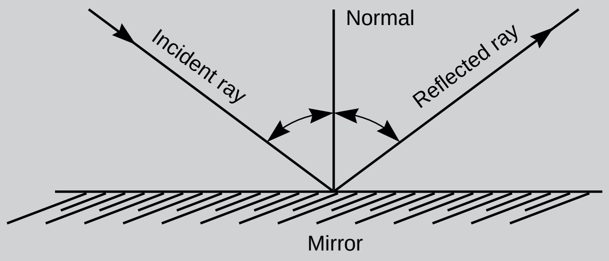
Figure 2. Schematic layout of the equal-path, fringe-stabilized interferometer used for grating exposure. Light from a single-mode laser, is divided into two paths by a beam splitter and passes, via small turning mirrors, spatial filters, larger turning mirrors, and lenses, onto the surface of a grating blank. The angle between the two beams fixes the groove spacing.

Reflecting Light Off Metal

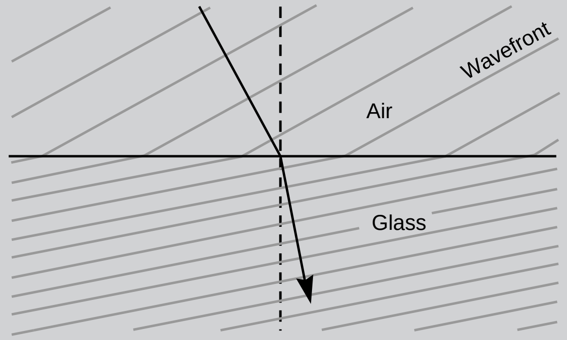
Traditional diffraction gratings, widely used in spectrometers to analyze broadband low-intensity light sources, have a corrugated metallic surface of precisely parallel periodic grooves. The metallic surface reflects the light, and the periodic groove structure diffracts the light, sending different wavelengths, or colors, back at different angles. For many decades, such gratings were produced by engraving with an extremely precise tool called a mechanical ruling engine. Today grating manufacturers often use holographic techniques, relying on the stability of continuous-wave laser wavefronts to provide the precision. Figure 2 shows a schematic diagram of our holographic exposure facility. A photosensitive surface is exposed to a standing wave pattern created by interfering two highly coherent laser beams. The latent image of the periodic interference pattern is then developed (essentially as photographic film is developed) to create a corrugated surface. Coating this grooved surface with a thin metallic film can create a highly efficient reflection grating. Alternatively, the pattern can be transferred into a more robust underlying dielectric substrate by chemical etching or ion etching

How a Diffraction Grating Works

Light is an electromagnetic wave that travels through free space in a straight line, or ray. When light waves encounter a surface, they change direction. If the surface is a mirror, nearly all the light is reflected; each incoming ray reflects at an angle equal to its angle of incidence.



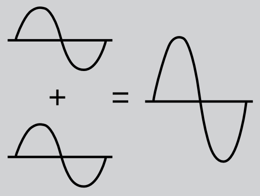
When the surface is smooth and transparent, such as a windowpane, most of the light will pass through. However, because wavefronts travel more slowly in glass than in air, the rays of obliquely incident light will become bent as they enter the glass.



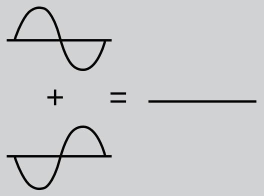
The refractive index of the material—the ratio of the speed of light in a vacuum to the speed in the material—determines how much bending (refraction) occurs.

Light also bends when it scatters from the edge of a small object; this is diffraction. When the light has a narrow range of colors, the scattered waves will interfere.

In some directions, wave crests will overlap and reinforce one another; this constructive interference will enhance the intensity of the light. In other directions, crests will match troughs, canceling one another as destructive interference and producing a dark region.



Reinforcement

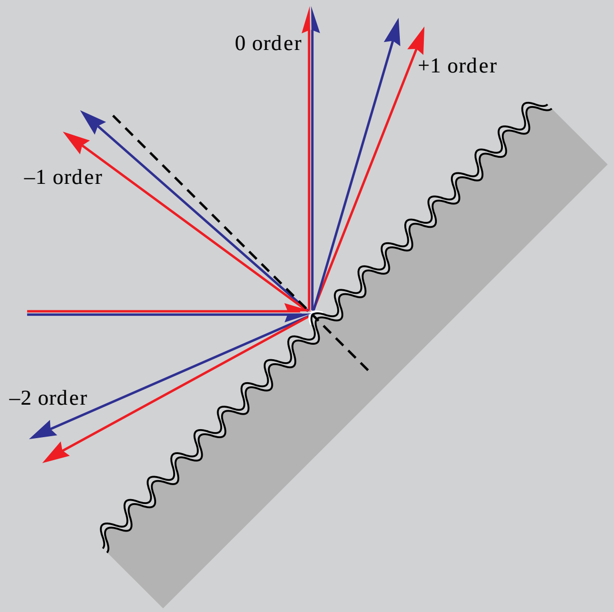


Cancellation

When the surface has periodic ridges (a grating), then an incoming single-color ray produces scattered rays (of the same color) at only specific discrete directions. Each of these directions is a diffraction order for the specified color and incident angle.

The color of the light is not changed by diffraction. However, blue light diffracts by smaller angles than red light, so that a ray of white light (blending many colors) will emerge from a grating with each constituent color diffracted into a different direction. The resulting display is the familiar rainbow of colors. The periodic grooves on the surface of a compact disk provide an everyday example of this phenomenon.

The color and direction of a light ray incident on a grating, together with the spacing of the periodic grooves, determines how many diffracted orders are present. If the grooves are far apart, then one color may emerge into many diffraction orders. If the grooves are closely spaced, as they are for our gratings, then only two orders occur: one emerges from the grating as it would from a mirror (the zero order), and the other order is retroreflected back along the incident direction (order –1).



When a collimated beam (a ray) of single-color light strikes a grating, the periodic grooves scatter the light into all angles. At certain angles, the outgoing waves add constructively to create an outgoing beam (a diffraction order). The outgoing wave has the same color as the incoming wave. If the incoming beam contains two or more colors, the outgoing angles differ for the different colors, and a multicolor beam is separated into single-color outgoing beams.

procedures. Transfer etching tends to produce rectangular or trapezoidal grating profiles from the original rounded patterns of developed photoresist (see Figure 3).

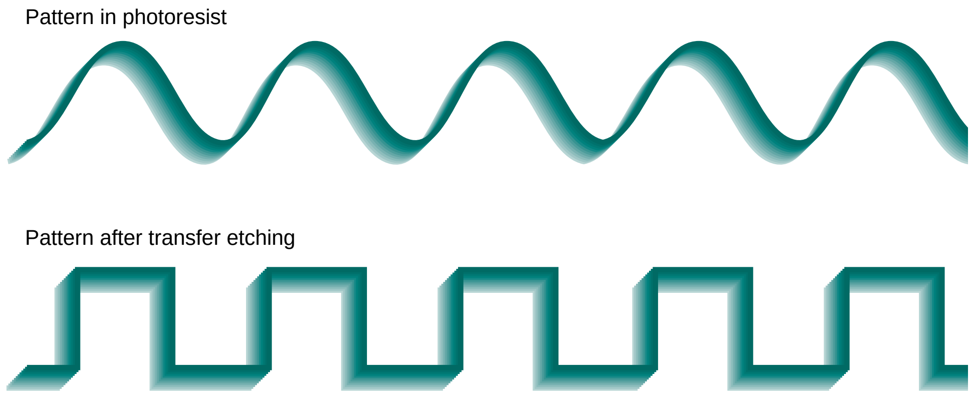


Figure 3. Schematic comparison of grating groove profiles before and after development of photoresist.

Metallic gratings have many useful attributes. A properly designed and carefully manufactured metallic coated grating can have a diffraction efficiency that exceeds 95% over a broad range of wavelengths (that is, more than 95% of the light is returned from the surface as diffraction into a single order). The behavior of a grating is primarily governed by the spacing and the shape of the grooves as well as by the optical properties of the metal. Gold, silver, and aluminum are typically used as coatings.

Because metallic diffraction gratings owe their highly reflective surface to the high conductivity of the metal, and the conductivity is relatively insensitive to wavelength, metallic gratings are inherently broadband devices. However, they have a low threshold for optical damage; heating of conduction electrons renders the surface susceptible to damage at fluences of around 0.8 joule per square centimeter (J/cm^2) for nanosecond laser pulses in the infrared and at much lower fluences for shorter wavelengths or shorter pulses. Metallic diffraction gratings have therefore been a limiting factor in the production of short, high-energy pulses.

Making Insulators Reflect

Because transparent dielectric materials are insulators, they lack the conduction electrons that make metals reflecting. As a result, transparent dielectrics have intrinsically higher thresholds for laser-induced damage than do metals. Moreover, multiple layers of different dielectrics have long been known to produce highly reflecting structures. In 1991, reasoning from this well-established fact, researchers at LLNL undertook to develop a grating design by the addition of a grating to a multilayer dielectric stack.

Whereas metallic gratings achieve high reflectivity as a consequence of conduction electrons, a multilayer dielectric stack of alternating high and low refractive index layers achieves reflectivity by interference: light is reflected from the succession of surfaces whose separation is designed so that waves traveling forward and backward will destructively interfere. Each interface between a high-index and low-index pair has approximately 4% reflection, but the aggregate of many layers can approach complete reflection of light (over a range of wavelengths).

The manufacture of high-efficiency multilayer dielectric gratings draws on several subsidiary technologies in optics and chemistry and requires careful control of a number of steps: the creation of a stack of dielectric films, each of a specified thickness; the uniform coating of a photosensitive layer; the creation of a very precise interference pattern in this layer; and the transfer of the latent image into a permanent corrugation pattern in a dielectric layer. The transfer etching may be performed by a host of standard lithographic techniques, including conventional wet etching, ion sputter etching, and reactive ion etching. The choice of technique is governed by the choice of dielectric material and the desired groove spacing and depth.

Demonstrating the New Concept

In 1992, LLNL teamed with Hughes Electrooptic Systems of El Segundo, California, to demonstrate these multilayer dielectric gratings. Computer modeling provided target designs. These computations included examining how a variety of groove shapes and multilayer properties affect efficiency;

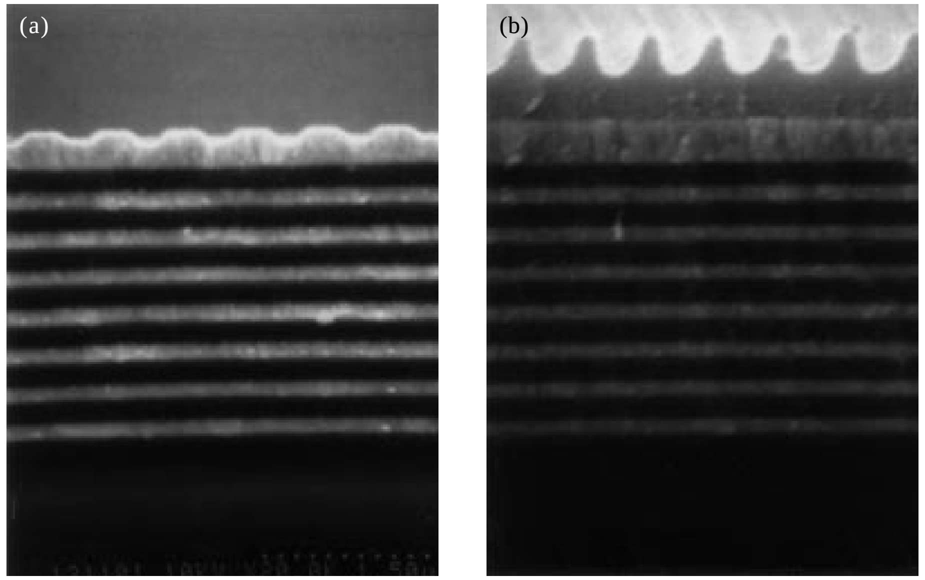


Figure 4. Scanning electron micrographs of two multilayer dielectric gratings: (a) one produced by ion etching, and the other (b) by the secondary layer technique.

for selected groove depths, diffraction efficiency exceeding 98% was predicted.

In 1993, for our first demonstration of this new type of grating, we sought extremely high efficiency in reflection for light with a wavelength of 1053 nanometers (1 nm = 10^{-9} m), the wavelength to be used in the 100-TW and petawatt lasers. We created a dielectric stack of eight pairs of high- and low-refractive-index materials deposited on borosilicate glass. Each layer pair was designed to provide high reflectivity. The grating structure was transferred into the multilayer by a multistep ion etching technique. Our computations indicated that grooves etched to the appropriate depth in the topmost, high-index layer should have an efficiency of 98%. The actual grating achieved a measured efficiency exceeding 97%.

We have continued the development of these gratings with a range of design objectives, various dielectric films, and gratings of larger size.

How the Gratings Are Made

A dielectric grating can be fabricated directly into the topmost layer of a dielectric stack, as shown in Figure 4a. This fabrication technique requires ion etching to transfer the grating pattern into the dielectric multilayer. It requires that the other layers in the stack be designed for use with the grating layer under consideration, since that layer is part of the stack.

An alternative method, called the secondary layer technique, is to fabricate a grating in a dielectric layer to be placed on top of an independently designed multilayer structure, as shown in Figure 4b. This method allows the multilayer stack to be designed either with or without the grating in place. The grating structure is constructed in a separate dielectric layer, of the necessary thickness, which is deposited on top of the multilayer. The grating pattern can be achieved by depositing the dielectric through a holographically produced mask, in photosensitive material directly, or by other lithographic techniques (e.g., lift off). As in the previous case, the grating shown in Figure 4b was designed to provide high diffraction efficiency at 1053 nm. It was fabricated in prepared photoresist on a conventional hafnium oxide/silicon oxide multilayer high reflector; it produced a diffraction efficiency of more than 96%.

Novel Grating Properties

Our primary motive for developing multilayer dielectric gratings was to enhance resistance to laser damage, an objective that has been realized. However, multilayer dielectric gratings have several novel properties that offer unique opportunities for new applications:

- The efficiency of a multilayer dielectric grating can be adjusted for any given wavelength and polarization by altering the phase retardation properties of the multilayer stack, the depth and shape of the grating grooves, and the beam's angle of incidence. We adjust these properties during manufacture to control the distribution of energy among the reflected, transmitted, and diffracted beams. Diffraction efficiency for specific incident radiation can be adjusted between 0.01% and 98%.
- The wavelength discrimination inherent in a multilayer stack makes it possible to build gratings that transmit or reflect light with high efficiency within a narrow optical wavelength band. A grating can be designed to have nearly any desired efficiency and bandwidth. This extreme optical selectivity, which is not possible with conventional metallic or bulk dielectric transmission gratings, allows a narrow spectral region to be selected to the exclusion of all others (see Figure 5).
- The damage threshold of our dielectric gratings for 3000 picoseconds (ps) laser pulses has been measured to exceed 5 J/cm^2, nearly ten times that of the best metallic gratings. For short pulses (0.1 ps), our standard multilayer dielectric gratings exhibit a damage threshold of approximately 0.6 J/cm^2, three times higher than the short-pulse damage threshold of commercially available metallic gratings. Further refinement of our multilayer design is expected to increase the short-pulse damage threshold to more than 1 J/cm^2. A grating that can withstand these high powers is essential to realize the compression of multikilojoule pulses that will be required for fast ignition of an inertial confinement fusion capsule.

Numerous Applications

Either independently or in combination, the unique capabilities of multilayer dielectric gratings allow new optical and laser products to be created. Manufactured in large size (a meter in diameter), these gratings are an enabling technology for the development of lasers with a petawatt of peak power and for the application of such high-energy lasers to inertial confinement fusion. Lasers that provide a petawatt of power in a picosecond may make it possible to achieve fusion using significantly less laser energy than currently envisioned. Useful fusion power could then be achieved perhaps years earlier than would otherwise be possible. (See p. 36 for a discussion of how the application of the 100-TW laser to the fast ignitor concept could accelerate our development of laser fusion.)

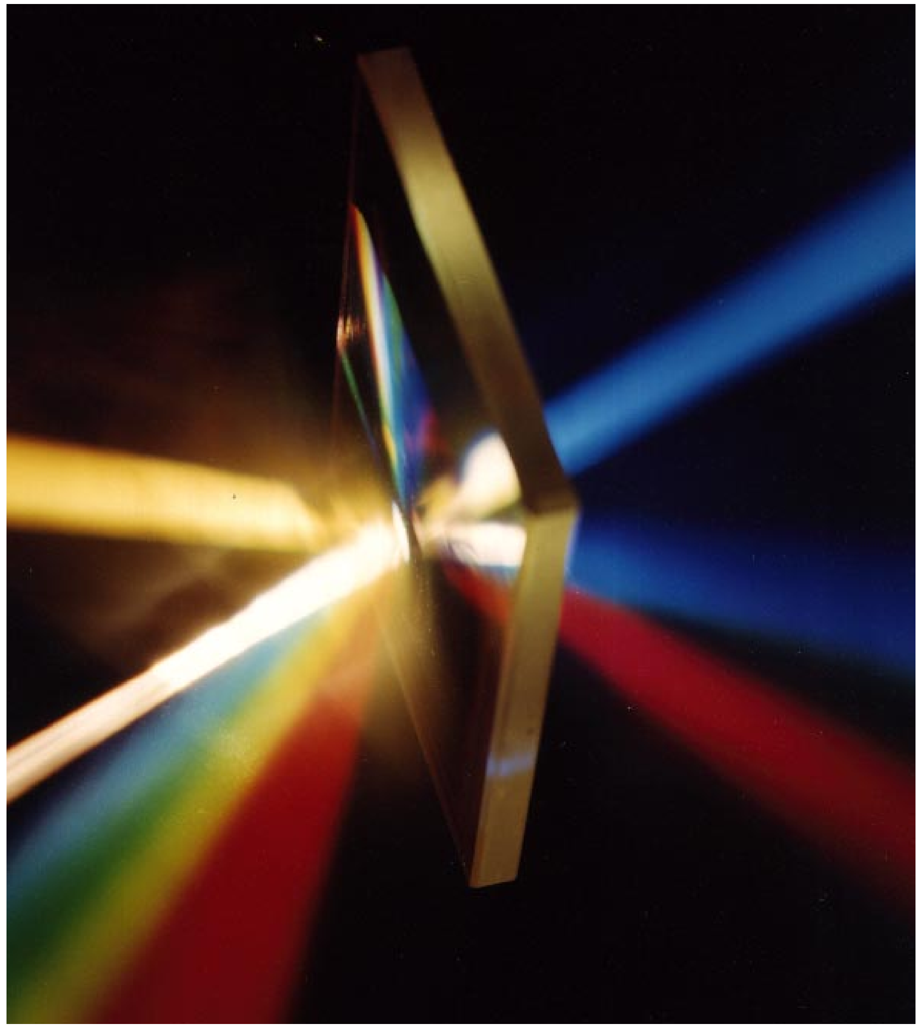


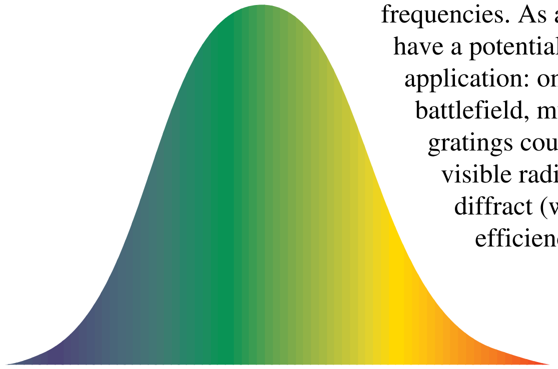
Figure 5. A multilayer dielectric diffraction grating designed to reflect yellow light, diffract broadband visible radiation (bottom left), eliminate all green and yellow light in the transmitted diffracted beam (at right), and transmit blue–green light. The grating pictured is 15 ¥ 20 ¥ 2.5 cm.

Multilayer dielectric diffraction gratings have many commercial applications. The high diffraction efficiency will find immediate use in commercial laser systems employing gratings for pulse compression, and the increased damage threshold will permit the size of the pulse compressor to fall below that of current metallic gratings.

The gratings' combination of high efficiency and high damage threshold for long pulses will make it possible to develop high-power, tunable, narrow-linewidth lasers using broadband solid-state materials with high-density energy storage, such as alexandrite, titanium-doped sapphire, and neodymium-doped glass. Compact lasers can now be made that have high pulse energies and narrow linewidth outputs that are tunable over the gain bandwidth of the laser material. This new type of grating will also extend high-efficiency diffracting structures into the ultraviolet region (to wavelengths below 220 nm) where the reflectivity of metallic coatings drops precipitously.

Because multilayer dielectric gratings can be designed with an arbitrary bandwidth to reflect some frequency components, transmit others, and diffract still others in either reflection, transmission, or both, it is possible to select a narrow spectral region with the grating while discriminating against all others. Such sensitivity will find immediate use in high-contrast spectrometers, where discrimination often must be one part per million and is currently achieved only by the use of multiple conventional gratings.

Because of their spectral selectivity, these multilayer dielectric gratings are discrimination filters. Specifically, we designed the gratings to reflect undesirable narrow-line optical radiation (e.g., laser radiation) while transmitting most other frequencies. As a result, they have a potential military application: on the battlefield, multilayer gratings could transmit visible radiation and diffract (with high efficiency) unwanted radiation from laser weapons or laser guidance systems. Finally, because the distribution of energy among the spectrally reflected, transmitted, and diffracted beams is controllable by adjusting the design of the multilayer and grating structure, we can use multilayer dielectric gratings as selective beam splitters in optical switches and distribution systems.



Summary

Our development of high-efficiency multilayer dielectric gratings is a technical innovation that opens the door to a host of new products and makes metallic gratings obsolete in many current applications. Its significance lies in the versatility of the device. By proper design, we can obtain a grating of almost any efficiency and bandwidth. For laser applications, the nearly tenfold increase in the optical damage threshold for long pulses over metallic gratings enables their use in high-power laser systems. These unique features, either independently or in combination, make possible the development of a new class of optical products.

We have demonstrated that such multilayer dielectric gratings can be produced, that they can reflect selected wavelength bands with high efficiency, and that they can be made in large sizes while maintaining high quality wavefronts. Manufactured in small size, these gratings can be used to create lasers with narrow linewidth and high pulse energy for such uses as directional beam splitters and efficient narrow- or broad-band filters.

Key Words: chirped pulse amplification; dielectrics; diffraction gratings–metallic, multilayer dielectric; petawatt laser; short-pulse laser.

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