High-efficiency, high-dispersion diffraction gratings based on total internal reflection

John R. Marciante
Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623

Daniel H. Raguin
Aprilis, Inc., Suite 200, 5 Clock Tower Place, Maynard, Massachusetts, 01754

Received September 22, 2003

We report a new class of high-dispersion immersed diffraction gratings for which the reflective nature of the diffraction is provided by the phenomenon of total internal reflection (TIR) regardless of grating tooth shape. Thus, the component can be fabricated from a single dielectric material and requires no metallic or dielectric film layers for high reflection diffraction efficiency. With the absence of metallic absorption, diffraction efficiencies of these TIR gratings can reach more than 99% for 15–20-nm spectral bandwidths, making them suitable for many laser-based technologies. © 2004 Optical Society of America


Diffraction gratings are an integral part of many modern optical systems, with applications in spectroscopy, display systems, and optical telecommunications components. Diffraction gratings have also found widespread use in the operation of laser systems; they provide wavelength selectivity for tunable lasers, pulse compression for ultrafast lasers, and power scaling for wavelength-combined lasers. Many types of diffraction grating have been designed and fabricated to induce peak performance from a host of properties, including dispersion, bandwidth, and efficiency.

Generally, a diffraction grating consists of a periodically varying boundary of period \( \Lambda \) between two dissimilar materials with refractive indices \( n_1 \) and \( n_2 \). For incident angle \( \theta_i \), diffracted angle \( \theta_m \) of the \( m \)th diffracted order is determined by a grating equation expressed as

\[
n_1 \sin(\theta_i) + n_o \sin(\theta_m) + \frac{m \lambda}{\Lambda} = 0, \tag{1}
\]

where \( \lambda \) is the vacuum wavelength of the light incident from material 1. Angles \( \theta_i \) and \( \theta_m \) are measured with respect to the grating normal, and \( n_o \) is either \( n_1 \) or \( n_2 \), depending on whether reflected or transmitted diffraction orders are analyzed. Whereas the spectral properties of the grating are determined solely by Eq. (1), the efficiency of the grating is determined by the profile of the periodic structure and requires rigorous vector wave modeling for accurate prediction.

Reflection gratings operate such that light incident from material 1 diffracts primarily back into material 1. For typical reflection gratings, material 1 is air and material 2 is a metal such as gold, silver, or aluminum. Absorption of light at the metallic surface reduces the maximum attainable diffraction efficiency to 75–95%, depending on the metal used and on the wavelength of the incident light. Additionally, this absorbed power turns into heat, which can be problematic or even catastrophic when sufficient optical power is incident upon the grating. Alternatively, dielectric transmission gratings can be combined with reflective dielectric stacks to provide a metal-free solution for high-power applications.

It has been proposed that for an immersed grating with material 2 being air and material 1 being a dielectric with index \( n_1 > 1 \), if the grating profile is shaped such that incident light reflecting off any facet of the surface is reflected by means of total internal reflection (TIR), then high-efficiency diffraction can be attained without a metallic coating. However, this process requires fine control over the grating profile, which must be drastically changed for fabrication of gratings with different functionalities, and it limits the angles of incidence that are allowable in terms of grating surface designs that can be practically fabricated.

In this Letter we describe a new class of diffraction grating that utilizes the broader phenomenon of TIR to generate high-efficiency reflective diffraction. This new TIR grating allows for the fabrication of immersed gratings without the use of metallic or dielectric coatings and with restriction on grating tooth shape.

As invoking the TIR phenomenon implies, no transmitted orders exist for a TIR grating. The condition that must be met for a TIR grating to exist is as follows: For an arbitrary angle of incidence of light incident from material 1, the grating period must be chosen such that the incident and diffracted angles all fall under the condition of TIR at the interface between the two materials. This condition is mathematically expressed as

\[
n_2/n_1 < | \sin \theta_j | < 1, \tag{2}
\]

where \( \theta_j \) represents any and all of the propagation angles of the incident or diffracted light in material 1. This can be readily seen from Eq. (1), in which the interchangeability of the term \( n_o \sin(\theta_m) \) in either material 1 or 2 is given by Snell’s law. Thus, if the TIR condition captured in expression (2) is satisfied, all diffracted orders will be reflective in nature, and no light will be transmitted. Embedded in expression (2) is the requirement that \( n_1 > n_2 \).

In many cases it is desirable to obtain high-efficiency diffraction for only a single diffracted order. In fact, expression (2) can be used to show that, for many materials, only a single diffracted order exists for a TIR...
grating. In the Littrow configuration, where the diffracted light retraces the same path as the incident light, the grating period must satisfy the inequality

\[ n_1 > \frac{\lambda}{2\Delta} > n_2. \tag{3} \]

Expression (3) is a simple combination of expression (2) and Eq. (1).

The conditions set above in expressions (2) and (3) limit the diffractive behavior of the grating such that a diffracted order into material 2 simply cannot exist. In fact, the conditions above that define the TIR grating are valid regardless of the nature of the grating profile. Thus, a grating with any tooth shape, e.g., sinusoidal, binary, trapezoidal, or blazed, is classified as a TIR grating, provided that expression (2) is satisfied.

Although, in general, material 2 can be chosen to be any dielectric material such that expression (2) is satisfied, the true value of such an immersed grating is gained if material 2 is chosen to be air. First, the limits set by expressions (2) and (3) are given the largest range when \( n_2 = 1 \). Second, and perhaps more importantly, such a grating is made from but a single material. No coatings need be applied, which simplifies the fabrication process significantly and subsequently reduces the cost of fabricating the grating.

Figure 1 depicts such a high-dispersion TIR grating. The light is incident upon the grating from within material 1 at angle \( \theta_1 \). With the grating period and the angle of incidence chosen such that expression (2) is satisfied, no light escapes into material 2 regardless of the grating tooth shape. The exact grating tooth profile will determine the power distribution among the various reflected diffracted orders, but no transmitted diffracted orders can exist.

To illustrate this TIR grating concept, consider a grating component made solely from fused silica, i.e., \( n_i = 1.450 \) and \( n_2 = 1 \), with incident light that has a vacuum wavelength of 1064 nm and is TM polarized (magnetic field perpendicular to the plane of incidence). In this example, grating vector \( \mathbf{K} \) is aligned such that it lies in the plane of incidence. The grating period allowed by expression (3) must be 367–532 nm long for high-efficiency Littrow TIR diffraction. Consider a binary diffraction grating with a 50% duty cycle and a period of 425 nm. For this grating the Littrow angle is 59.69° when \( \lambda = 1064 \) nm, and the diffraction efficiency for TM-polarized light is optimized when the depth is 152 nm.

In Figs. 2 and 3, rigorous coupled-wave analysis\(^{30}\) is used to compare the diffraction efficiencies of the \( m = -1 \) order of an all-glass TIR grating and that of a conventional metallic grating (material 1, air; material 2, aluminum) with similar dispersion. In general, the dispersion of a grating is calculated as \( d \theta_m / d \lambda \). For an immersion grating the angle of incidence at which the light enters material 1 can be arbitrarily designed such that the net dispersion of this interface combined with the grating can be larger or smaller than the dispersion of the grating itself. To compare gratings of equivalent dispersion, this effect must be mitigated by having the diffracted beam exit material 1 at normal incidence. The dispersion for an immersed grating is then defined as

\[ D = \left| \frac{d \theta_m}{d \lambda} \left( \frac{d \theta_{m,\text{air}}}{d \theta_m} \right)_{\text{Normal}} \right| = \left| \frac{m}{\lambda \cos(\theta_m)} \right|. \tag{4} \]

The first derivative is calculated from Eq. (1). The second derivative is calculated from Snell’s law and evaluated at normal incidence for calculation of grating performance alone. For the TIR grating to be used in our calculations, where \( m = -1 \), the dispersion is calculated to be 4.66 mrad/nm. A conventional aluminum grating of the same dispersion for \( m = -1 \) is obtained when the period is 574 nm. For this grating the Littrow angle is 67.95° when \( \lambda = 1064 \) nm, and the diffraction efficiency for TM-polarized light is optimized when the depth is 152 nm.

Figure 2 shows the diffraction efficiencies of the TIR and metallic gratings for TM-polarized light as a function of incident wavelength for fixed angles of 59.69° (TIR) and 67.95° (metallic) as well as for an...
The TIR grating provides additional flexibility for wavelength alteration of the grating tooth profile. Thus, diffraction efficiency never exceeds 5% without significant alteration of the grating tooth profile. However, for the aluminum-covered grating the TE diffracted order can be made to perform nearly identically to that for TM light. The efficiency limits at angles of incidence less than the Littrow angle are due to the diffraction of TE light from the TIR grating can be obtained at the Littrow angle. The efficiency limits at angles of incidence lower than the metallic grating in an angular bandwidth of ±0.5°. With a slight modification in the grating duty cycle, the TIR grating has better diffraction efficiency than the metallic grating over an 83-nm window, exceeding 99% within a 19-nm bandwidth. Such a high-performance low-loss dispersive element is highly suitable for intracavity operation in many types of laser systems.

Figure 3 shows the diffraction efficiencies of the TIR and metallic binary diffraction gratings with the same dispersion as a function of angle of incidence for TM-polarized incident light with a wavelength of 1064 nm, for the grating parameters given in the text. The angle of incidence on the horizontal axis is given with respect to the respective Littrow angle for each grating.

Angle of incidence that varies according to the Littrow angle for the particular wavelength of interest. For a fixed angle of incidence (solid and short-dashed curves) the TIR grating has higher diffraction efficiency than the metallic grating within a 113-nm window. In fact, the diffraction efficiency of the TIR grating is greater than 99% in a 15-nm bandwidth and reaches unity at the design wavelength. At wavelengths shorter than 950 nm, the efficiency increases again as the first and zeroth orders exchange energy, but it is never so high as shown near the design wavelength. For wavelengths greater than 1150 nm (TIR) and 1110 nm (metallic), the diffracted order becomes evanescent. In the Littrow case (dotted and long-dashed curves), the TIR grating works with higher efficiency than the metallic grating over an 83-nm window, exceeding 99% within a 19-nm bandwidth. Such a high-performance low-loss dispersive element is highly suitable for intracavity operation in many types of laser systems.

In conclusion, we have invented a new class of immersed diffraction grating that does not require metallic or dielectric layers to provide reflection. The classification of the TIR grating is independent of grating tooth shape and relies on a single design rule to maintain the performance described herein. Such a grating can be made from a wide variety of materials but garners the most benefits when but a single material is used, with no additional material deposition required. Diffraction efficiencies of 100% can be attained for high dispersion, with significant spectral and angular bandwidth over 99% diffraction efficiency for laser-based applications.

This research was performed at Corning Rochester Photonics Corporation. The authors thank Tasso Sales for the use of his numerical vector diffraction code. J. R. Marcianite’s e-mail address is johnm@lle.rochester.edu.

References