multilayer coating, these gratings could be fabricated with an adjustable bandwidth. High diffraction efficiency (>98%) into the first order was theoretically achievable by controlling the depth of the grooves and the design of the multilayer itself.

Due to fabrication issues, we concentrated on designs with the grating in the top layer of the multilayer. The grooves are formed in the top layer via an interferometric exposure in photoresist followed by transfer etching (see Fig. 1). In general, the transfer etching may be performed by a host of standard techniques, *e.g.*, conventional wet etching, or reactive or sputter ion etching. The choice of dielectric material, groove spacing, and groove depth will determine the appropriate technique for pattern transfer. Examination of various fabrication techniques led to a collaboration with Hughes Electrooptic Systems to develop these multilayer gratings by ion etching.

An alternate fabrication approach is to produce the grating structure on top of the multilayer by deposition or directly in the photopolymer. For low power applications, the photoresist profile can serve as the final grating or it can serve as the mask for deposition of a more damage resistant material.

To date, we have achieved a diffraction efficiency in reflection exceeding 98% at 1053 nm with gratings manufactured by both techniques.[3] The frequency selectivity of these gratings is demonstrated in the image on the cover where the grating serves as a broadband diffractor in reflection, a high efficiency yellow reflector (zero order), a high efficiency transmitter in the blue-green, and a notch filter in the transmitted diffracted order.

The damage threshold of our multilayer oxide gratings is over 5 J/cm^2 for 1 nsec pulses, nearly an order of magnitude greater than metallic gratings. For 100 fsec pulses, the damage threshold drops to 0.6 J/cm^2, compared to between 0.2 and 0.4 J/cm^2 for gold gratings used in the 800 to 1100 nm range. Further development is expected to increase the femtosecond damage threshold to over 1 J/cm^2.

References

1. M.C. Hutley, *Diffraction Gratings*, Academic Press, San Diego, Calif. (1982).
2. R.D. Boyd *et al.*, "High efficiency metallic gratings for laser applications" Appl. Opt. **34**, 1697 (1995).
3. M.D. Perry *et al.*, "High efficiency multilayer dielectric gratings" Opt. Lett. **20**, 940 (1995).

Low-Threshold Optical Switching in Non-uniform Nonlinear Distributed Feedback Structures

Stojan Radic, Nicholas George, and Govind Agrawal, The Institute of Optics, University of Rochester, Rochester, N.Y.

Photonic band structure of a nonlinear distributed feedback (DFB) device can be altered by increasing the intensity of the input light. Local changes in refractive index of the DFB structure lead to a variety of all-optical effects[1, 2] including switching, multistability, low-velocity energy transfer, pulse generation, and pulse shaping. However, a strictly periodic nonlinear DFB (NLDFB) must be operated at prohibitively high intensity levels, requiring both high-power sources and low-absorption nonlinear materials. As an illustration, a millimeter long GaAs device would require switching intensities ~1 GW/cm^2. We have recently shown that by introducing non-uniformities in the DFB structure, either in a continuous or in a discrete fashion, the required switching intensities can be reduced by several orders of magnitude.[3, 4] A generalized non-uniform DFB design shown in Figure 1a includes tapering, chirping, and multiple phase-shifted regions. In addition, the material nonlinearity is allowed to vary along the device length, accounting for non-uniform doping levels.

In our search for an optimal non-uniform nonlinear structure, we have developed a new design method. The method, referred to as the generalized transfer matrix (GTM) method, provides an extremely fast, semi-analytic characterization of an arbitrary nonlinear DFB device. Figure 1b illustrates the use of the method in characterizing the transmission of a nonlinear λ/4-shifted structure. This structure, extensively used in linear photonic design,

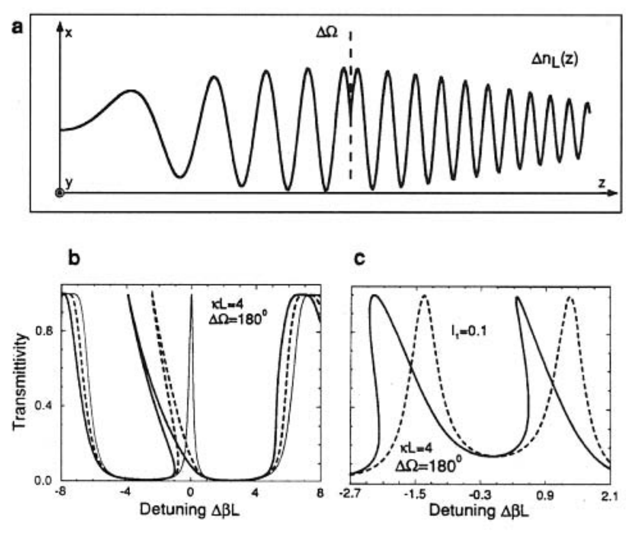

Figure 1 (right). a) Linear index profile of non-uniform DFB includes taper, chirp, and multiple phase shifts. b) Transmission characteristic of λ/4-shifted nonlinear DFB device for different input intensities: $I_{in}=0.2I_C$ (heavy solid curve), $I_{in}=0.1I_C$ (dashed curve), and $I_{in}=10^{-5}I_C$ (thin solid curve). c) Transmission characteristic of multiple phase-shifted NLDFB. Phase shifts of $\Delta\Omega=\pi$ are positioned at z=0.35L and z=0.65L. Solid curve corresponds to $I_{in}=0.1I_C$, while dashed curve corresponds to $I_{in}=10^{-5}I_C$. Critical intensity parameter I_C is defined in Ref. 4.

exhibits a highly resonant behavior, characterized by a narrow transmission peak in the middle of the Bragg stop band. By operating in close vicinity of the transmission peak, one can achieve an all-optical switching and limiting behavior at intensity levels that are up to three orders of magnitude lower than those of comparable uniform NLDFB. A multiple-phase shifted device shown in Figure 1c, exhibits an even more interesting behavior. By controlling both the location and value of the phase shifts, one can selectively control the position and the form of the transmission peaks simply by tuning the input intensity.

While phase-shifted structures are clearly superior to comparable uniform NLDFB, they are still not an optimal solution. Switching intensities can be reduced by an additional order of magnitude by combining the phase-shifted DFB with a co-directionally coupled waveguide. Such a structure represents a four-port nonlinear device with potential applications for extremely low-intensity all-optical switching, routing, and pulse generation. It is not difficult to foresee the first practical diode-driven devices that include optimal NLDFB design and use highly nonlinear materials that are now becoming available. Our current work is concerned with both characterization and practical realization of these devices.

References

1. W. Chen and D. L. Mills, "Optical response of nonlinear multilayer structures: Bilayers and superlattices," Phys. Rev. **B36,** 6269-6278 (1987).
2. C. Martijn de Sterke and J. E. Sipe, "Launching of gap solitons in nonuniform gratings," Opt. Lett. **18,** 269-271 (1993).
3. S. Radic *et al.*, "Theory of low-threshold optical switching in nonlinear phase-shifted DFB structures," J. Opt. Soc. Am. B **12,** 671-680 (1995).
4. S. Radic *et al.*, "Analysis of nonuniform nonlinear distributed feedback structures: GTM method," IEEE J. Quantum Electron. **31,** 1326-1336 (1995).

Optical Characterization of Photonic Microstructures

Thomas F. Krauss and Richard M. DeLaRue,
Optoelectronics Group, Glasgow University,
Glasgow, Scotland.

Microstructured photonic materials are expected to show full photonic bandgap (PBG) effects if the periodic arrangement of the photonic lattice is appropriately chosen and there is sufficent refractive index contrast. A PBG crystal can be seen as a three-dimensional Bragg reflector for photons. Such materials may eventually lead to a new generation light emitting devices with ultralow threshold, high efficiency, and very low noise.[1] The fabrication of suitable three-dimensional photonic crystals at optical wavelengths is difficult and may not be practical for some time, which is why our work is focussed on lower-dimensional patterns embedded in a waveguide structure. The waveguide approach provides a means of characterizing photonic lattices[2, 3] and can also be exploited directly in increasing the functionality of optoelectronic devices, *e.g.*, lasers, filters, and nonlinear elements.[4]

Referring to a "normal" grating as a one-dimensional phótonic bandgap structure may sound somewhat exaggerated, but one should keep in mind that "normal" gratings, *e.g.*, as in DFB lasers, usually use refractive index contrasts of at most 1%, whereas photonic bandgap structures demand a contrast of greater than 2:1. Diffraction losses, *i.e.*, coupling to radiation modes require serious consideration, particularly since the third dimension (conveniently assumed infinite in most 2-D calculations) only extends to, at most, 1μm in a semiconductor waveguide structure. These losses arise because modal confinement is limited to the semiconductor region, whereas in the air region the light is not confined and some degree of out-of-plane diffraction occurs. We have developed a waveguide structure that aims to minimize these losses by confining the mode near the surface and by etching very narrow gaps into the semiconductor, thereby maintaining as much guiding as possible.

We performed transmission measurements on third order 1-D lattices (420/470 nm period, 100 nm gap) with a tunable Ti:sapphire laser. The measurement clearly shows the band edge on the long-wavelength end of the bandgap for two different grating periods (see Fig. 1) and is the first demonstration of PBG effects in a

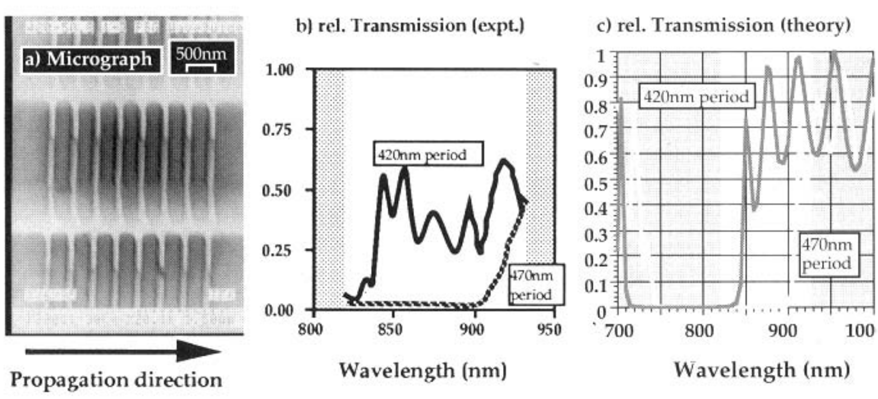

Figure 1. Experimental results of a third order 1-D PBG struction and comparison with simulation. (a) Physical structure, 420 nm period, 100 mm airgaps, etched 0.9 μm deep. (b) Normalized transmission through two different waveguide structures (420 and 470 nm period) measured with a tunable Ti:sapphire laser. (c) Simulation of the properties of the same structure. The wavelength range accessible in the measurement is highlighted.