8-Wavelength DBR Laser Array Fabricated with a Single-Step Bragg Grating Printing Technique

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Abstract—**An 8-wavelength DBR array for narrow channel wavelength division multiplexing (WDM) has been fabricated with a new technique for printing first-order Bragg gratings using a phase mask and a conventional incoherent source. All the distributed gratings were printed in a single photolithographic step with a slightly modified mask aligner. We demonstrate excellent wavelength control for channels separated by as little as 0.8 nm. Many advanced photonic devices relying on gratings like quarter-wave shifted DFB lasers and WDM components can potentially be manufactured with this technique in a simple and cost-effective way.**

THE practical deployment of wavelength division multiplexed (WDM) systems will require integrated multiwavelength laser sources using gratings with several different pitches in close proximity on a single chip [1]. At present there is no technique for fabricating such arrays suitable for manufacturing. Holographic exposure has become the standard grating fabrication technique for guided-wave optoelectronic devices such as DFB or DBR lasers. While offering rapid, large area processing of the entire wafer, this method has severe limitations when more complex grating configurations are required. Electron-beam lithography has proven to be a powerful tool, but the long writing time required to create these patterns raises serious questions about the manufacturability of devices when several inch wafer processing is contemplated. Okai *et al.* [2] have demonstrated the use of a machine-ruled phase and amplitude grating as a mask that can be illuminated with a laser beam to generate two self-interfering beams in its near-field, and thus provide the required high contrast grating pattern. Recently, this technique has been extended using an *e*-beam generated pure phase mask in quartz [3], [4]. The extra degree of freedom given by the *e*-beam writing of the mask makes it possible to include several grating pitches with close lateral spacing on the same mask, in addition to arbitrary chirps and phase-shifts. Moreover, the photolithographic technique can be further simplified by substituting a conventional Mercury arc lamp to the laser source, allowing the gratings exposure to be carried out with a slightly modified mask aligner in a standard clean-room environment. In this letter, we demonstrate the fabrication of an 8-wavelength DBR laser array with a single grating exposure step performed with such a phase mask illuminated by incoherent light. We also examine issues associated with the mask fabrication, fidelity of phase-shift reproduction, and requirements for incoherent exposure.

The principle we employ is shown in Fig. 1, and is similar to a method recently demonstrated using a laser and replicas of a mechanically ruled grating [2]. A beam at wavelength λ is incident at an angle θ_i on the surface which has a corrugation at period Λ_g. On the far side of the wafer the incident beam is transmitted at angle θ_i, but a first-order diffracted beam is also generated at the angle θ_d given by $\theta_d = \sin^{-1}(\lambda/\Lambda_g - \sin(\theta_i))$. The period Λ_g is short enough that the only transmitted beams are the 0th order beam at θ_i, and the first-order diffracted beam at θ_d. These two beams then function just as in the two beam holographic method, causing a fringe pattern below the mask at the spatial period of the grating. This mask is used in a contact mode so that variations in the local pitch or phase shifts introduced in the mask are properly transferred to the resist on the sample being exposed, and the example shown in the figure includes a $\lambda/4$ phase shift.

We have used direct write *e*-beam lithography (EBL) and reactive ion etching (RIE) to fabricate square-wave gratings in quartz substrates which serve as pure phase masks in the near-field holographic printing of gratings. While similar structures have been demonstrated using direct-write-on-wafer [5], [6] the parallel printing technique proposed here avoids the slow serial writing process.

The example in Fig. 1 includes an abrupt half-period phase shift as might be found in a $\lambda/4$-shifted distributed feedback laser. Fig. 2 illustrates a modeling of the interference pattern in the intensity of the transmitted and diffracted beams as they propagate away from the mask surface. The particular case chosen here has a 240 nm-pitch grating with a half-period shift, illuminated by 364 nm highly coherent light. The fields are approximated after the mask by numerically evaluating the Fresnel integrals in the Fresnel diffraction approximation. One can see from the peak and valley alignments the obvious result that, away from the slightly smeared phase-shift location itself, the phases of the two regions are properly

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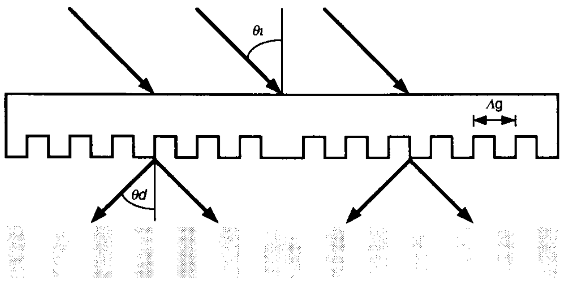

Fig. 1. Schematic diagram of near field printing of grating like pattern by interference of zero- and first-order diffracted beams.

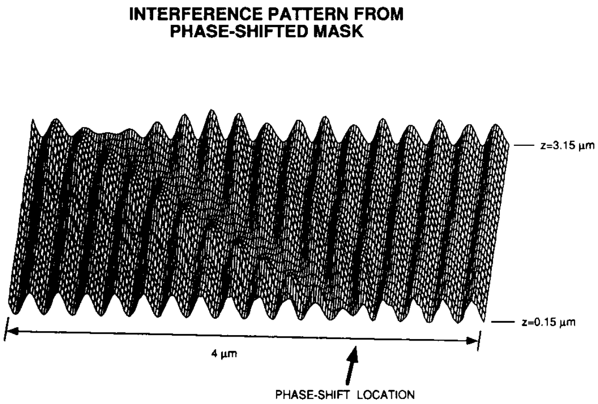

Fig. 2. Spatial evolution of near-field intensity modulation using a phase-grating mask with abrupt shift in the grating near the arrow.

shifted. While the Fresnel approximation to the steep-angled propagation after the mask is obviously of limited validity, it does qualitatively suggest that the printing technique can be used to reproduce local grating features when used in the near field.

Since a near-field use only requires local spatial coherence and limited temporal coherence from the illumination source, we have examined the feasibility of an exposure with a conventional Hg arc lamp. Commonly available interference filters have a bandwidth of about 10 nm and are sufficient to isolate the Hg triplet lines at 365 nm. However, they can not separate out the individual three lines, respectively at 365.02, 365.48, and 366.33 nm. These lines are also broadened by atomic collisions in the high pressure arc lamp. Therefore, as a worst case approximation, a lamp with an interference filter should have a linewidth of about $\Delta\lambda = 2$ nm (FWHM). Simple calculation based on a Lorentzian lineshape indicate that the maximum path difference for a fringe visibility of 90% is 7 μm. The sample-mask distance L corresponding to this path difference is in fact much larger since our typical Bragg angle θ_i is close to 45°.

Spatial coherence is limited by the finite dimension of the arc, which makes it less ideal than a point source. The light collected from the Hg lamp by the collimating optics will thus be imperfectly collimated, resulting in a full angle spread $\Delta\theta = a\ lf$ for a source of spatial extent a and a focal length f. Each ray impinging at $\theta_i + d\theta$ on the mask will create its own fringe intensity pattern at the substrate plane with a slight phase shift depending on the incidence angle. The minimum intensity $S_{\min}$ (resp. the maximum $S_{\max}$) is computed by summing up all the contributions from gratings generated by the slightly misaligned illuminating beam:

$$S_{\min} = \int_{-\Delta\alpha}^{\Delta\alpha} \sin^2 u\, du = \Delta\alpha - \frac{\sin 2\Delta\alpha}{2}$$

$$S_{\max} = \int_{\pi/2-\Delta\alpha}^{\pi/2+\Delta\alpha} \sin^2 u\, du = \Delta\alpha + \frac{\sin 2\Delta\alpha}{2} \qquad (1)$$

where $\Delta\alpha = L\pi\Delta\theta/\Lambda$ is the maximum dephasing of the fringe pattern at the substrate plane and Λ is the grating pitch. The fringe visibility is thus given by $V = S\max - S\min/S\max + S\min = \sin(2\Delta\alpha)/2\Delta\alpha$. Using a commercially available 100 W Hg lamp with a 0.25 mm arc size, collimating optics with $f = 50$ mm, and a first order grating pitch $\Lambda = 2400$ Å, we find that fringe visibility over 90% requires $L \leq 12$ μm. This is not a very stringent requirement and shows that the coherence obtained from a typical mask aligner with a short arc Hg source with an interference filter added is sufficient despite the submicron nature of the fringe period. Since diffraction efficiency of the mask is strongly polarization dependant, a polarizer should also be added to select orthogonal polarization.

We have applied this phase mask technique to the fabrication of an array of four-section DBR lasers [7] at 8 different wavelength. The devices combined a 840 μm long gain section, a 120 μm phase section, a 180 μm grating section, and a 100 μm integrated monitor section. A 100 GHz (corresponding to 0.813 nm) frequency spacing between lasers was chosen for compatibility with dense WDM systems. Comprehensive details about the phase mask fabrication can be found in [3]. Our starting substrate was a chromium coated fused silica photomask blank. Windows were first opened in the chromium for the gratings at each device site by conventional photolighography. The e-beam exposure of the grating was then performed on a trilayer photoresit, followed by a transfer in the quartz by reactive ion etching. The pitch difference between successive grating in the mask was 1.27 Å, the base pitch being 2437 Å.

Fig. 3 shows the pitch measurement performed on the finished mask, showing an experimental pitch progression of 1.33 Å. The ratio of the first order diffracted beam to the zero order transmitted beam was 0.5, which is enough to generate a fringe pattern with a visibility of 94%. Fig. 4 shows a scanning electron micrograph of wet etched gratings in InP obtained after photolithographic exposure with the modified mask aligner and Hg lamp source, attesting of the high quality of the gratings obtained.

The fabricated laser had thresholds of less than 30 mA, and Fig. 5 shows the wavelength distribution of the lasers. The lasers where biased at approximately 50 mA. The

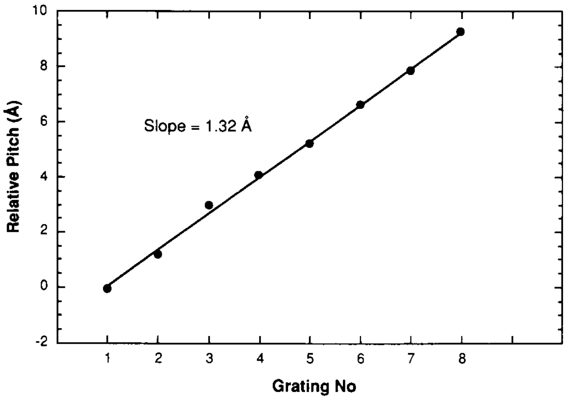

Fig. 3. Pitch progression between adjacent gratings on the *e*-beam generated phase mask.

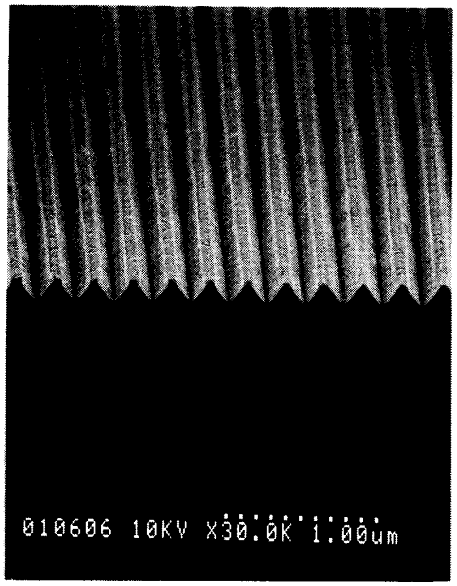

Fig. 4. Gratings etched in InP after phase mask lithographic exposure with a conventional incoherent Hg source.

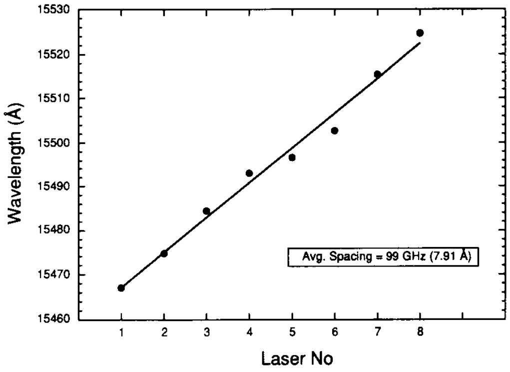

Fig. 5. Wavelength distribution of the eight lasers in the array (no tuning currents applied).

average frequency spacing was 99 GHz, within 1 GHz of the assigned goal. The scatter is due in part to random mode placement within the more-evenly spaced Bragg bands, and further fine tuning using current injection in the phase and grating sections is possible. We achieved essentially ideal characteristics with less than 2 mA in any tuning section.

In conclusion, we have demonstrated a technique for generating gratings for advanced photonic circuits using an *e*-beam generated phase mask. The grating exposure is greatly simplified by the use of contact printing and conventional mercury arc lamp illumination. Furthermore, the *e*-beam writing of the phase mask allows to include multiple grating pitches and arbitrary phase shifts in a single exposure step. Finally, this technique is suitable for high volume production since it avoids the long writing time of direct *e*-beam write. An 8-wavelength DBR laser array with close (100 GHz) channel spacing has been fabricated using this technique, demonstrating low thresholds and excellent wavelength control. This grating fabrication technique may find important applications for the future generations of lightwave components, particularly for phase-shifted DFB's and WDM components.

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