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Surface-micromachined free-space micro-optical systems containing three-dimensional microgratings

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Free-space micro-optical systems on a chip containing three-dimensional microgratings have been demonstrated using surface-micromachining technique. The micrograting is integrated with a rotary stage, a collimating micro-Fresnel lens, and an edge-emitting laser held by three-dimensional alignment structures on a single Si substrate. Diffraction patterns for various grating rotation angles are observed. Another optical interconnect module consisting of three cascaded microgratings is also demonstrated. The micrograting is a basic building block for many micro-optical systems and is very attractive for applications in microspectrometers, free-space optical interconnect, optoelectronic packaging, and wavelength-division multiplexed integrated micro-optical systems. © *1995 American Institute of Physics.*

The surface-micromachining process has been successfully applied to the fabrication of various three-dimensional micro-optical elements such as micro-Fresnel lenses and micromirrors as well as micropositioners and rotary stages.[1–3] In addition, it has also been utilized to realize the hybrid integration of 8×1 arrays of vertical-cavity surface-emitting lasers (VCSELs) and micro-Fresnel lenses for free-space optical interconnect applications.[4,5] These micro-optical elements can be utilized to construct monolithic free-space integrated optics. Most previous research on integrated optics has focused on guided-wave approach in which active and passive optical devices were connected by passive waveguides.[6] On the other hand, free-space optics provides advantages not realizable by guided waves. For example, free-space optical interconnect allows one to implement sophisticated three-dimensional interconnection schemes to relieve the communication bottlenecks in massively parallel systems, in addition to the advantages of large spatial bandwidth (diffraction-limited output) and high throughput.[7]

To build an entire free-space optical system on a single substrate, three-dimensional optical elements with optical axis parallel to substrate are needed. It is desirable to fabricate these elements using a batch processing technique such as microfabrication to reduce the cost and assembly time. However, the topography of three-dimensional elements is not compatible with standard microfabrication and lithographic processes. By using microhinge technology,[8] it is possible to implement three-dimensional free-space optical systems on a monolithic platform by first fabricating the optical elements with planar processes and then folding the optics plates into three-dimensional structures. This approach combines the advantages of integrated optics design and micromachining processing. In addition, on-chip actuators[9,10] could be integrated on the same chip to provide precision optical alignment, close-loop feedback control, or opto-mechanical switching.

In this letter, we report on the demonstration of two micro-optical systems containing three-dimensional micro-gratings fabricated by the surface-micromachining technique. In the first system, a three-dimensional micrograting has been integrated with a rotary stage, a passively aligned edge-emitting laser, and a collimating micro-Fresnel lens. Diffraction patterns of the micrograting are confirmed with theoretical simulations when the on-chip rotary stage is rotated by 70°. The second system consists of three microgratings cascaded in two stages to perform optical fan-out functions. In these micro-optical systems, all the optical elements are fabricated monolithically except the diode laser source, which is hybrid integrated with passive alignment. Since grating is an important building block for many optical systems, the current devices can be applied to microspectrometers, tunable lasers with external grating cavity, wavelength division multiplexed (WDM) components and systems, and free-space optical interconnect.

The schematic diagram of the micro-optical system consisting of a passively aligned edge-emitting semiconductor laser, a collimating micro-Fresnel lens, and a micro-grating on a rotary stage is shown in Fig. 1. The semiconductor laser is side mounted with junction plane perpendicular to the substrate and aligned to the micro-Fresnel lens by surface-micromachined precision positioners.[11] The micro-Fresnel lens has a focal length of 500 μm. The micrograting is integrated on a rotary stage and is located at 5 mm away from the lens. The optical axis for both passive and active components are defined to be 254 μm above the surface of the Si chip. This optical system is ‘‘prealigned’’ at the design and

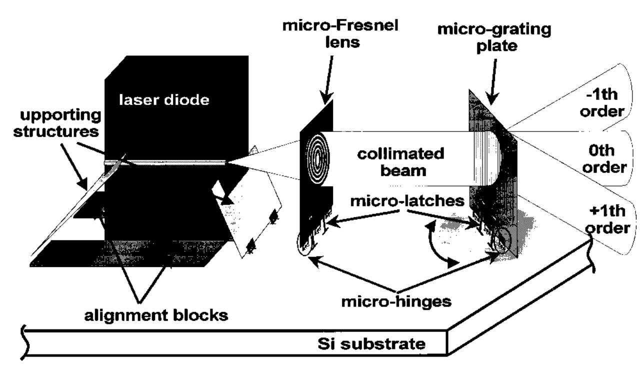

FIG. 1. The schematic diagram of the micro-optical system consisting of a passively aligned edge-emitting semiconductor laser, a collimating micro-Fresnel lens, and a micrograting on a rotary stage.

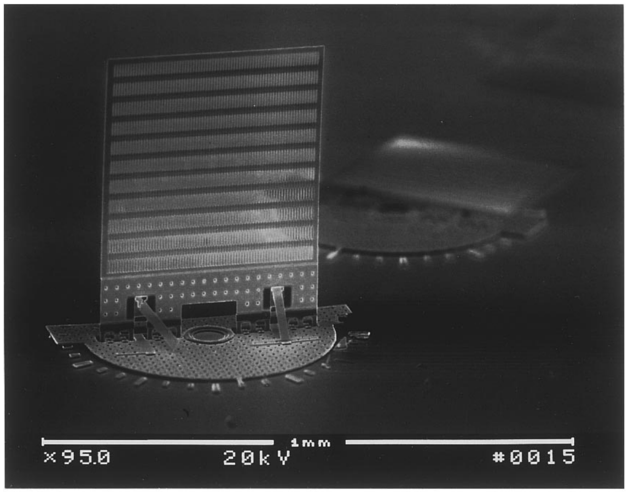

FIG. 2. The SEM of the micrograting on a rotary stage.

layout stage. The scanning electron micrograph (SEM) of the micrograting on a rotary stage is shown in Fig. 2. The micrograting is realized using microhinges and spring-latches similar to the micro-Fresnel lens.[1] However, the hinges of the grating are fixed on the rotatable plate instead of Si substrate. The rotatable plate itself is implemented by a suspended polysilicon plate whose center is fixed by a polysilicon hub similar to that of the micromotor.[12] The micrograting has a pitch of 5 μm and is coated with a thin layer of aluminum to enhance the diffraction efficiency. Indicators are patterned around the rotatable plate at every 10° to identify the angular position of the grating.

In this experiment, the output light from the laser diode is first collimated by the micro-Fresnel lens, and then passes through the grating. The diffraction pattern is monitored by a charge-coupled device (CCD) camera while the grating is rotated. The CCD image of the diffraction patterns are shown in Fig. 3(a) The zeroth and first-order diffraction patterns are clearly observed. Figure 3(b) shows the first-order diffraction angles versus the grating angle when the grating is rotated from −35° to +35°. The relationship between the diffraction angle and grating angle is related by

$$\alpha = 90° - \theta - \cos^{-1}\left(\frac{k_i \sin(\theta) + k_g}{k_i}\right)$$

and

$$\beta = \cos^{-1}\left(\frac{k_i \sin(\theta) - k_g}{k_i}\right) + \theta - 90°,$$

where α, β are the positive and negative first-order diffraction angles, respectively, and k_i is the magnitude of wave vector of the incident light and k_g is the magnitude of k vector of the grating. As shown in Fig. 3, the experimental results agree very well with the theoretical values.

The schematic diagram of the optical interconnect module consisting of three cascaded microgratings is shown in Fig. 4. The grating is fabricated by a similar process, except that the hinges are fixed on the Si substrate. The micrograting is 600 μm wide, 900 μm tall, and has a grating pitch of 4 μm. The gratings in the optical interconnect module are

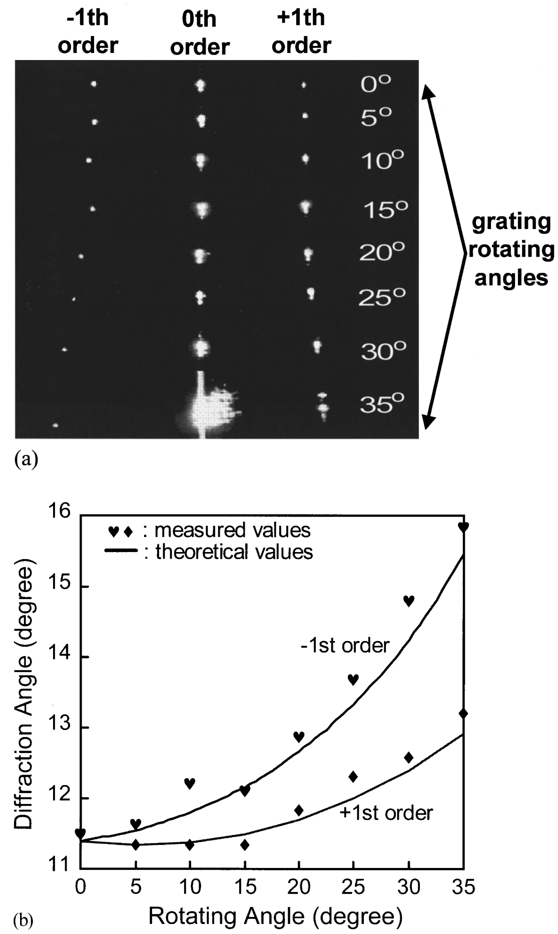

FIG. 3. (a) The zeroth and first-order diffraction patterns at the various grating angles and (b) the first-order diffraction angles vs the grating angle when the grating is rotated.

separated into two stages, the first stage consists of one grating and the second stage consists of two gratings arranged side-by-side. The incident light passes through the first stage and splits into three beams: zeroth order, positive first order, and negative first order. The zeroth order beam does not pass through any additional grating, and each of two first order diffracted beams pass through one additional grating at the second stage and are further split into three beams. At the output of the optical module, we will obtain three beams that

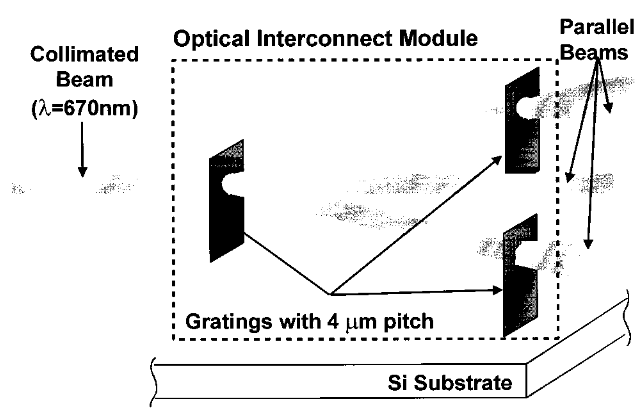

FIG. 4. The schematic diagram of the optical interconnect module consisting of three cascaded microgratings.

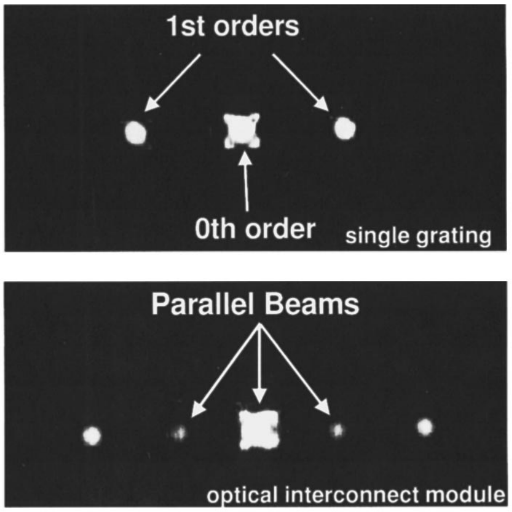

FIG. 5. The CCD images of the far-field diffraction patterns of a single grating and the entire optical interconnect module.

are parallel to the incident light. One is the zeroth-order diffracted beam from the first stage and the other two are doubly diffracted first-order beams. This optical interconnect module is designed for visible light at the wavelength of 670 nm. Figure 5 shows the CCD images of the far-field diffraction patterns of a single grating and the entire optical interconnect module. This optical module performs the function of optical fan-out, which can be used for optical distribution of high-speed data and clocks. Optical modules consisting of multiple microgratings are potentially able to achieve more sophisticated optical switching and interconnection functions. They can be combined with other micromachined micro-optical components such as micro-Fresnel lens, rotary stage, micromirror, and beam splitter to implement various free-space integrated optical systems.

In conclusion, two free-space integrated micro-optical systems containing three-dimensional microgratings have been demonstrated by surface-micromachining technique. A rotatable grating has been integrated with a semiconductor edge-emitting laser source and a collimating micro-Fresnel lens. Optical diffraction patterns are successfully observed as the grating is rotated. An optical interconnect module with cascaded microgratings is also demonstrated. These micro-optical systems are very compact, and can be ''prealigned'' in the design stage. The integrable three-dimensional micro-gratings are very useful for applications in microspectrometers on a chip, optical interconnect, and wavelength-division multiplexed (WDM) micro-optical systems.

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