Micro-opto-mechanical grating switches

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Abstract

This paper reports the design, fabrication, and testing of a Micro-opto-mechanical grating switch driven by electrostatic actuator for fiber-optic communication applications. It consists of two bounded silicon wafers. One input fiber with a hemispherical lens at its end and three photodetectors are mounted on the upper wafer. A movable platform with two gratings and one mirror are fabricated on the lower wafer. When the movable platform is at a certain position, the input beam can be split into three beams by the gratings. The reflectivity of the mirror is about 85% while the efficiency in the three different order is 29%, 26%, and 26%. The switching speed is about 500 μs. Details of the grating switching design, theoretical analysis, fabrication and experimental results are presented in this paper. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

One attractive feature of optics especially for communication and information processing is its ability to transmit huge amounts of digital stream in parallel. Fiber optics switches are used to reconfigure the high-speed digital fiber-optics network. For example, a passive optical network (PON) or hybrid electronic/optical network needs various types of optics switches. The rapid growth of fiber-based local area networks has created a large demand for low-loss, low-cost, reliable, and mass-producible fiber optics switches.

The significant advantage of using Microelectromechanical Systems (MEMS) for optics switches is its small size, low cost, and high reliability and stability [1,2]. Micro-opto-mechanical gratings are very attractive for implementing wavelength division multiplexing (WDM) switches, as reflection grating is used to disperse incident light into angular directions determined by the incident light’s wavelength and the construction properties of the grating. Variable blaze gratings (VBGs) [3] have adjustable blaze angles with a fast time response (less than 10 ms) are suitable to be designed as $1 \times N$ multiplexer using MEMS technology. It provides the important capability of high density digital transmission communication with a band width as high as 2.5 Gbps. Diffraction grating without any movable mechanical part has been used to produce a diffraction spot pattern for optical interconnection [4]. The type of interconnection is mainly used for computing network. Two other type of diffraction grating switches of used in broadband optical network have been reported [5,6].

This paper proposes a micro-opto-mechanical grating/mirror switch that is a programmable add/drop multiplexer to be used as a spatial terminal switch for single-wavelength optical local network or passive optical telecommunication network. Firstly, the design of a grating/mirror switch with one-input and three-outputs used as a miniaturized fiber-optics network terminal switch is described. The design includes grating structure, mechanical actuators and electronic signal processing. The main effort is concentrated on improving the diffraction efficiency of the interested diffraction order. Then, the simulation results of the grating diffraction efficiency is shown.
Lastly, the fabrication process is explained and experimental results are compared with theoretical analysis.

2. General considerations of optical grating

The grating interference orders result when light reflected off each grating element combines constructively in the far field. Normally, the reflective diffraction gratings are divided into three different types grating such as flat grating, tunable grating and variable blazed grating.

2.1. Flat gratings

The flat reflective grating producing constructive interference is shown in Fig. 1. The locations of constructive interference regions are sequentially numbered as interference orders 0, 1, ..., \(m\). The light reflected off grating elements adds destructively in the region between orders. Because the phase of light arriving at the location of interference order is dependent on the wavelength, the location of the orders depends on the wavelength of the incident light. The direction of a particular order, \(\theta_m\), resulting from normally incident light is given by:

\[
\theta_m = \arcsin \left( \frac{m\lambda}{P} \right)
\]

where \(m\) is the interference order number, \(\lambda\) is the wavelength of the source, and \(P\) is the period of the grating.

The spatial intensity distribution is:

\[
I(\Psi) = \text{cons} \times \left( \frac{Lk}{N\sin(\pi\Psi)} \frac{\sin(\pi k\Psi)}{\pi k\Psi} \right)^2
\]

where \(N\) is the total number of grating lines, \(w\) is the width of the reflection part, \(k\) is the fill factor \((k = w/P)\), \(L\) is the total width of the grating \((L = NP)\), and \(\Psi = P(\sin\theta + \sin\theta_m)/\lambda\).

The grating Eq. (2) describes both the formation of spectrum and the formation of diffracted orders. Some insight into the way in which the various orders are formed may be gained by considering the vector sum in each case. Actually, the vector sum goes round one complete revolution for the first order, two for the second, and three for the third order, etc. Since the second half is suppressed, this gives rise to an amplitude of 1/2 in the zero order, 1/2\(\pi\) in the first, 0 in the second (and all even orders) and 1/6\(\pi\) in the third (and 1/2\(m\pi\) in all odd orders). In this particular case, the intensity efficiency in the zero order is thus 1/4, in the first 1/4\(\pi\), in the third 1/36\(\pi^2\). However, if we control the variation of optical path across each individual groove, then any order can be chosen (Fig. 2). Fig. 3 is the curve of the diffraction intensity \(I\) (without considering the constant factor \(L\) and \(k\)). The effect of the finite width reflective line gives out a filtering window. When \(k = 0.4\) and \(N = 6\), namely \(-2, -1, 0, +1\) and \(+2\) diffraction orders are visible only. The other diffraction orders are missing. When \(\Psi = m\), there is a bright fringe and \(I\) reaches its maximum. The simple relationship

\[
-2P/\lambda \leq m \leq 2P/\lambda
\]

comes from \(-2 \leq \sin\theta + \sin\theta_m \leq 2\), that is, the pitch of the grating has an influence on the visible diffraction fringes.

2.2. Tunable gratings

In grating design, when the grating pitch \(P\), the incident beam wavelength \(\lambda\) and the angle \(\theta_1\) are fixed, the diffraction efficiency of the different orders is determined by the grating line profile. The major consideration for the design of an individual grating element is to ensure a minimum power in \(+2\) order so that the most of input power can be distributed in 0 and \(\pm 1\) orders uniformly. The two-layer tunable grating is shown in Fig. 4. The value of \(\Psi\) will vary depending on the position of the upper Poly 2 grating. Four positions, which span a full
The diffraction intensity distribution of the finite width reflection line ($k = 0.4$, and $N = 6$).

Fig. 3. The diffraction intensity distribution of the finite width reflection line ($k = 0.4$, and $N = 6$).

period, are indicated for the following three values of $\gamma$: (a) $\gamma = 0 \mu m$, (b) $\gamma = 2 \mu m$, (c) $\gamma = 4 \mu m$, and (d) $\gamma = 6 \mu m$. The Poly 1 grating suspended by spring flexures can be pulled down electrostatically. The grating intensity distribution of the diffracted beam is then dominated by two parameters: the fill factor $w_rP$, and the depth $h$. Diffraction efficiency is symmetrical about the fill factor $w_rP = 0.5$ in the range of $0 < w_rP < 1$.

Fig. 5 shows the simulation results of the relative optical power $P$ of the diffracted beams vs. the grating groove depth $h$ with respect to different values of the fill factor $w_rP$. The grating parameters are in the vicinities of $w_rP = 0.4$, and $h = 1.8 \mu m$, respectively, for grating one. In order to facilitate the fabrication process, the final parameters of grating are chosen as $w = 1.5 \mu m$, which indicates $w_rP = 0.375$, and $h = 1.8 \mu m$. The grating design is considered compatible with the polysilicon fabrication process and design rules. The corresponding relative power distribution is 29% for 0 order, 26% for $\pm 1$ orders and is less that 4% for $\pm 2$ order. The optimized simulation of the diffraction efficiency vs. the grating groove depth $h$ for the optimal condition of $w_rP$ being 0.375 is shown in Fig. 6.

2.3. Variable blaze gratings

Blazing is contouring individual grating elements and can be used to improve the ratio of light diffracted in a specific direction to the incident light, increasing the intensity of the light diffracted into a specific interference order. VBGs is operated by adjusting the blaze angle of each slat so that the specular reflection of the incident light matches a particular interference order that is shown in Fig. 7. For normal incident light, the blaze angle required to select a particular interference order $m$ is given by:

$$\theta_i - \phi = \theta_m + \phi$$

where the blaze angle $\phi$ is measured with respect to a plane parallel to the face of the grating. For example, VBGs blazed grating parameters are designed as the pitch $P = 8 \mu m$, tilt angle $\phi = 6.9^\circ$, total grating lines $N = 6$, and the incident light wavelength $\lambda = 1300$ nm, the incident angle $\theta_i = 0$ (normal incident). The main energy is blazed to the 3rd diffraction order and $k = \cos \phi = 0.99$, and the diffraction intensity distribution is shown as Fig. 8. It is clear that most of the energy is focused on the only one fringe ($\pm 3$ diffraction order), all the other diffraction orders are not visible. Micromachined VBGs is used to improve the frequency sensitivity of these spectral analyzers. The VBGs have higher diffraction efficiencies than typical transmission grating, and the high diffraction effi-

Fig. 4. The tunable grating profile.

Fig. 5. Diffraction efficiency vs. the grating groove depth $h$ for the 0 and $\pm 1$ orders and different aspect ratio $w_rP$.

Fig. 6. Diffraction efficiency vs. the grating groove depth ($w_rP = 0.375$) for the 0, $\pm 1$, $\pm 2$ orders.
ciency increases the strength of diffracted light on photodetector array elements of optics switch.

3. Optical grating switch design

Optical fibers are an attractive medium for signal transmission in optical communication as well as in optical metrology. There is an increasing need for higher versatility of fiber-optic systems with special requirements for reconfiguration, variable access to one or N channels. These requirements can be met by an implementation of fiber-optics switches of various types. For each particular application, there are well-defined parameters to be met by the switch with respect to: the number of input and output channels, insertion loss, cross-talk, switching speed, temperature, and vibration stability. The principle of all-optical switching scheme uses micro-optical components that are translated laterally from optical beams in order to accomplish beam deflection. A number of elements or combination of elements such as mirrors, prisms, and gratings, can deflect incoming beams. As agile switching is required for most of the applications, quick displacements have to be guaranteed by the mechanical actuators. As a separation of the single beams is achieved by deflecting the input beam, the angular overlap of the deflected beams, which subsequently enter different output channels, has to be small. For a Gaussian beam with a waist radius \( w_0 \), a wavelength \( \lambda \) and a numerical aperture \( n_0 \) given by \( n_0 = \lambda / \pi w_0 \), the overlap \( \eta \) of a beam deflected by an angle \( \theta \) with an undeflected beam with waist radius \( w_0 \) is given by [7–9]:

\[
\eta = \exp \left( -\frac{\theta^2}{\theta_0^2} \right).
\]  

Therefore, the cross-talk \( \chi \) of the beam is given by:

\[
\chi = 10 \log \left( \exp \left( -\frac{\theta^2}{\theta_0^2} \right) \right).
\]

In some communication networks where cross-talk below \(-50 \text{ dB}\) is required, the deflection angle \( \theta \) has to exceed \( 3.4 \theta_0 \).

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![Fig. 7. The blazed grating profile.](image)

![Fig. 8. The intensity distribution of a blazed grating vs. the diffraction angle (3rd order).](image)
3.1. Optical grating/mirror switch

The advantages of the concepts are basically due to the discrete or continuous steering ability of the various concepts. Discrete beam steering is accompanied by low required positioning accuracy with respect to the switching element that decreases the requirements on the actuator. The micro-gratings and micro-mirrors can construct 1 = N switches to steer an incoming collimated beam continuously and two-dimensionally. The switch route signals from one channel to a number of output channels with varying numbers of output channels depending on the concrete situation. The 1×N switches can be used to build up complex networks as well. A diffraction grating can diffract a monochromatic incident beam into several orders. The diffraction angles and the diffraction efficiency, i.e. the ratio of light diffracted in a specific order to the incident light, can be changed by structure parameters of the grating and the wavelength of the incident beam. Their optimal values will be determined by the diffraction equation as follows:

\[ m\lambda = P (\sin \theta_i + \sin \theta_m), \quad m = 0, \pm 1, \pm 2, \pm 3, \ldots, n \]

where \( m \) is the diffraction order, \( \theta_m \) is the diffraction angle, \( P \) is the grating pitch, and \( \lambda \) is the incident beam wavelength. The value of \( \lambda \) is taken as 1300 nm, and the value of \( P \) is taken as 4 \( \mu \text{m} \) in favor of fabrication. When the angle \( \theta_i \) equals to 23°, the diffraction beams of the 0, ±1, ±2 orders can exist, and the −2 order beam counter-strokes back to the direction of the incident beam. Thus this useless beam is automatically made inactive. We do not need to suppress it by absorbing or masking.

3.2. Device configurations

A grating switch can be designed as shown in Fig. 9. The proposed 1×3 grating switch consists of two wafer switching platforms. One input fiber with hemispherical end and one 3-PIN photodetector are mounted on the upper wafer platform. The hemispherical end acts as a lens to focus the laser source into a 40 μm spot. In the bottom wafer platform, two reflective gratings with size of 30×50 μm² are etched and coated with gold. A mirror of 30×50 μm² is placed between these two gratings. As the diameter of the diffraction beam at the upper platform is about 100 μm, the distance between two adjacent photo-detectors should be set larger than 200 μm to prevent the overlap and interference of the diffraction beams from the adjacent diffraction orders. The exact distance between two photodetectors is actually determined by the incident angle \( \alpha \) of laser beam and the distance \( H \) between upper and bottom wafer platform. Further consideration is required to determine the positions of all the three photodetectors. Our initial choice of \( \alpha \) is 20 ∼ 25° and \( H \) is 100 ∼ 200 μm.

The gratings and the mirror are supported by four folded beams and driven by two comb-drivers. As shown in Fig. 10, the supporting beams have a U shape and are connected to the frame close to its center. The incident beam is focused on the surface of one grating element. It is equally transmitted to all three-output photodetectors 1, 2, and 3 located at the upper wafer platform. The center of
the gratings and mirror is driven to the working position using $-25 \, \mu m$ to $+25 \, \mu m$ large displacement ($N = 6, P = 4 \, \mu m$, thus $L = 24 \, \mu m$). When the switching platform is displaced $+25 \, \mu m$ driven by the comb-driver, the input laser beam is incident onto the mirror. It is well known that the zero order diffraction angle is equal to the corresponding reflection angle, and the reflected beam reaches only photodetector Output 2. The simulated curve of voltage/displacement and compared with experimental results using IntelliCAD™ are shown in Fig. 11. A fair agreement is obtained as soon as the exact dimensions (as measured by SEM) of the electrodes gap are used. The spring constant is extracted by considering the resonant frequency of the structure. It may be seen that the results given by the simple plane capacitor approximation considerably underestimate the force.

4. Fabrication process and experimental results

The fabrication of the grating/mirrors uses three-layer-polysilicon and wafer to wafer bonding process. The gratings, the mirror and the actuator are fabricated on to the bottom wafer using the three-layer-polysilicon process as shown in Fig. 12. The two wafers are integrated using wafer to wafer bonding process. The gratings and mirror are constructed using surface micromachined polysilicon process. MUMPs offers three patternable layers of polysilicon, and two sacrificial layers of doped glass on a base layer of silicon nitride. A top layer of gold is used as the reflective surface for the grating. All polysilicon depositions are made by low-pressure chemical vapour deposition (LPCVD) with fine-grained polycrystalline silicon at 580°C. The fabrication of the grating and the mirror, including the electrostatic comb-drive, requires two levels of polysilicon. The first polysilicon layer provides a voltage reference plane and electrical interconnection, while the remaining two polysilicon layers form the mechanical structures. After fabrication, the device is released by removing sacrificial glass layers in a bath of 49% hydro-fluoric acid for 3.5 min followed by a short rinse in deionized water. The two wafers can then be bonded together along with active devices such as optics fiber and photodetectors onto a silicon optics switch chip. For prototype testing epoxy gluing is suitable to assemble both optical platforms.

The grating switch experimental set-up is shown in Fig. 13. The experimental system set up consists of a diode laser, a zoom beam expander, laser focusing lens, 2-D translation and rotation stage and a photodetector. Measured reflectivities were obtained in air with a He–Ne laser operating at a wavelength of 1300 nm. The grating switch chip is fixed on the 2-D translation stage. The lens is able to focus the expanded collimated beam to 15 $\mu m$. The rotation stage is used to control the incident angle of the input laser beam. The measured relative diffraction powers are 29% for 0 order, 26% for +1 order, 26% for $-1$ order, and 4% for $+2$ order and are in good agreement with theoretical analysis.

The actuator could switch from the $+25 \, \mu m$ to the $-25 \, \mu m$ position by applying of $+25 \, V$ on the two control electrodes, sufficiently low to be controlled by CMOS circuitry.
The resonance frequency, with an almost full span deflection, is measured at 1760 Hz, corresponding to a switching time lower than 500 μs. The frequency compare well with the theoretical value of 1797 Hz given by IntelliCAD™ and with the 1779 Hz obtained by the Rayleigh method. Of course, the theoretical calculation have to use the revised value of the beam width (1.75 μm) as measured by SEM on the fabricated device.

5. Conclusions

The design and fabrication of a micro-opto-mechanical grating switch using three-layer polysilicon surface micro-machining process is developed. Based on theoretical diffraction analysis and grating parameters optimization, grating line profile is determined as: \( w = 1.5 \ μm \) \((w/F = 0.375)\) and \( h = 1.8 \ μm \). The corresponding relative power distribution in percentage of input beam power is 29% for 0 order, and about 26% for +1 orders. The switching speed is below 500 μs. The prototype of the 1 × 3 programmable add/drop multiplexer is successfully demonstrated. Further work on analyzing the influence of convergent beam on grating diffraction and on different fabrication processes of gratings with different profiles will enable the optimization of the grating/mirror switch to be widely used in passive optical communication network.

References


Biographies

Ai Qun Liu received his PhD in Applied Mechanics from National University of Singapore (NUS) in 1993. His MS degree in Applied Physics and BEng degree was in Mechanical Engineering from Xi’an Jiaotong University. He was among those who started MEMS research activities in 1994, when he was assigned to explore and lead the MEMS research and development work in the DSO National Laboratory. His earlier MEMS projects are for military applications. In 1997, he jointed IMRE, National University of Singapore, as a senior research fellow, to drive and build up MEMS core technology. His research interest is optical and RF MEMS technology in information/communication applications, and in continuing work on positive optical network (PON) telecommunications systems, have implemented MEMS technology in a number of fiber optics related devices, such as micro mirrors/gratings OXCs and add/drop multiplexers. RF MEMS and electronic interface circuitry are also his major contribution area.

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