MEMS gratings and their applications

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ABSTRACT
Grating plays an essential role in various optical systems owing to its unique dispersion properties. In recent years, there is increasing demand to miniaturize optical systems for a wide range of field applications. Therefore, the integration of diffraction grating with MEMS technology provides an efficient way to build truly miniaturized optical systems. Till now, MEMS diffraction gratings have mainly been explored in two directions, namely MEMS scanning gratings and MEMS tunable gratings. MEMS scanning gratings are constructed with a variety of MEMS actuators to drive a grating platform to scan across the target, and they play a significant role in various scanning systems. Meanwhile, the dispersive properties of grating scanners make them attractive in wavelength sensing applications, including spectrometers and hyperspectral imaging systems. Tunable gratings typically employ MEMS actuators to dynamically change the diffraction properties, thus tuning its wavelength sensitivity for a specific application. Thus, this review will introduce these two types of MEMS gratings in detail and evaluate their efficiency and advantages in various fields.

KEYWORDS
MEMS; diffraction grating; grating scanners; tunable grating

1. Introduction
In recent years, the continuous development of optical techniques has made it more efficient and effective to understand and explain scientific knowledge in different fields, such as in modern life science and remote sensing. Therefore, novel and innovative optical systems attract wide research and industrial interest to meet the increasing demand for various applications. The diffraction grating plays an essential role in numerous functional optical systems to disperse the incident light to a spectrum of associated lines or steer the incident light to a specified direction by employing a periodic structure. Many methods have been explored to construct an efficient grating architecture, and microelectromechanical system (MEMS) seems to be a promising technology considering the trend of miniaturizing optical systems. MEMS technology typically allows the integration of multiple electrical and mechanical functionalities within a small chip, and thus MEMS gratings become a potential candidate for future portable devices. Advanced manufacturing technology, such as ion etching, also permits the fabrication of grating structures on glass with compact size and low cost, but the produced gratings has fixed and limited functionalities. Compared with MEMS gratings, external driving sources are required to modulate the properties of these traditional gratings for different application scenarios, hence increasing the overall size of...
resulted systems. Till now, MEMS diffraction gratings have mainly been explored in two research architectures, namely the scanning grating and the tunable grating.

The light scanning architectures have seen a wide range of application fields, including remote sensing, manufacturing, security, and consumer electronics. Traditional scanning systems are mainly built on rotating or oscillating mechanical mirrors that are limited in performance and are hard to integrate into a compact system. Thus, much research effort has been made to construct compact scanning systems using MEMS scanners, with MEMS grating being one of the most commonly adopted MEMS scanner. In the area of MEMS scanning grating, the grating structures are generally implemented on a scanning platform actuated by MEMS actuators. In this way, the orientation of grating lines can be changed by in-plane or out-of-plane MEMS motion, hence leading the diffracted laser beam to complete the target scan trajectory. Compared with traditional scanners, MEMS scanning gratings have unique characteristics in terms of combining diffraction/dispersion with scanning. Hence, MEMS scanning gratings provide a solid foundation for the development of new applications, such as scanning endoscopic probes. A special type of MEMS scanner, called optical phased array (OPA), is used to steer light by generating phase shift between each emitter in a two-dimensional device array. MEMS-based OPA device gets wide applications in light detection and ranging systems (LiDAR), owing to the high steering speed and steering efficiency.

Different from grating scanners, tunable grating is another important research topic where the diffraction properties of the resulted grating device can be modulated in a dynamic process. Such modulation is generally achieved by using MEMS actuators to change the grating period or the grating profile. This modulation can tune the sensitivity of the system for a target wavelength, thus making it attractive in wavelength-dependent applications, such as spectroscopy and tunable lasers. In addition, the tuning of grating structures can generate different types of modulation to allow the tunable grating to serve as an efficient light modulator or sensor.

Currently, many research demonstrations exist on the construction of scanning grating and tunable grating for a wide range of applications. Therefore, this paper is going to review these grating architectures and provide guidelines for anyone who aims to design efficient MEMS gratings for specific applications. This paper is organized in the following way: Section 2 will give a fundamental introduction of grating structures. Section 3 and Section 4 will each review the two types of MEMS grating devices mentioned. Each section firstly gives a brief description of the fundamental working principle of typical grating architectures, followed by introducing its related applications to indicate the potential and efficiency of such grating. Section 5 is going to summarize the properties of reviewed MEMS gratings and also give a brief comparison.
2. General architectures of MEMS grating

As mentioned, the grating is typically designed with periodic structures that can disperse the incident light to different directions. Figure 1(a) indicates the basic architecture of grating structures consisting of a large number of periodically distributed grating lines. When a polychromatic light beam is directed onto the grating, a spectrum can be produced for analyzing the properties of the incident light. So the diffraction grating covers a wide range of application fields, including spectrometers, monochromators, wavelength division multiplexing devices, and many other optical instruments. For monochromatic light, the grating can produce an array of regularly spaced beams at different directions, so it can also be used as a laser scanner by integrating with external actuators. The direction of diffracted light beam is determined by the diffraction grating equation below:

$$\sin \vartheta_i - \sin \vartheta_n = \frac{n \lambda}{d}$$

where $\vartheta_i$ is the incident angle, $\vartheta_n$ is the $n$th order diffraction angle, $d$ indicates the grating pitch, and $\lambda$ represents the wavelength of the incident light. In addition, $n$ is the diffraction order noted by integer values. It can be seen that the grating pitch is a crucial parameter of grating structures to determine the angular separation between the diffraction orders. More specifically, a small period creates large angular separation, and the grating pitch is usually designed according to the application requirement and the applied fabrication method. The shape of the grating profile is another primary parameter that will affect the diffraction efficiency and the relative power of each diffracted order. Two grating profiles are commonly adopted in the construction of MEMS grating devices, including the binary gratings and the blazed gratings, as shown in the inset of Figure 1(a). The binary grating can be easily designed and fabricated through MEMS technology but with limited diffraction efficiency compared with the blazed grating. For blazed gratings, larger angular separation is generally achievable with a larger blaze angle. It should also be noted that the surface quality of grating devices should be ensured for satisfactory diffraction efficiency. Currently, a variety of gratings is commercially available for different wavelength ranges but with fixed characteristics. So these commercial gratings get limited applications in these scenarios where adjustable properties of gratings devices are required, such as micro-spectrometers. Thus, MEMS gratings are more desirable in field applications considering that the usage of MEMS actuators can tune the diffraction properties of the gratings in scannable or tunable system architectures. To drive the diffracted beam along a target trajectory, MEMS scanning gratings utilize MEMS actuators to change the orientation of the grating lines. Figure 1(b) indicates that the diffraction properties can be changed through the modulation of the grating pitch, which is the
basic working principle of pitch-tunable gratings. It should be noted that the modulation of grating profiles can also change the diffraction properties of grating devices. If a larger deflection is introduced in MEMS tunable grating, the duty cycle (represented by $d$ in Equation 2), defined as the ratio of the grating width to the grating pitch, will vary significantly to change the achievable diffraction efficiency, given in Equation 2:

$$
\eta = \left( \frac{\sin (n\pi d)}{2n\pi} \right)^2 + \left( \frac{1 - \cos (n\pi d)}{2n\pi} \right)^2
$$

(2)

3. MEMS scanning grating architecture

In recent years, MEMS scanners have been rapidly developed to overcome the limitation of traditional mechanical scanners, such as galvanometric scanners. These MEMS scanners provide a competitive edge over traditional scanners in terms of the capability of miniaturization, low power consumption and good performance under resonant driving. This paper focuses the attention on grating scanners that implement periodic grating structures on a MEMS scanning platform. A variety of MEMS actuation methods have been explored to drive the scanning platform. During the driving process, the plane of grating structures will be changed to modulate the incident angle of the incoming light on the MEMS grating structures, hence achieving the target scan trajectories. Based on the applied motion types, MEMS scanning gratings can be further divided into two subcategories, i.e., the in-plane and the out-of-plane scanning gratings. This part will then introduce and evaluate the typical architecture of each subcategory using different MEMS driving methods, and much attention is focused on the parameters that determine the scanning performance. More specifically, a higher scanning frequency is preferable for MEMS scanners to speed up the scanning process, while a larger scan angle usually gives a larger field of view or better scan resolution. It should be noted that the dynamic deformation of the grating structures adversely impacts its optical performance, and therefore the rigidity of scanning grating devices should be ensured to maintain the flatness of resulted scanners during the scanning process. A special type of scanner, MEMS OPA device, will also be introduced in this part. The potential applications of each grating structure are also described to evaluate their performance.

3.1. Out-of-plane MEMS scanning gratings

The out-of-plane motion of grating scanners is generally obtained by tilting the platform implemented with grating structures. Tilting the grating platform will change the incident angle of incident light on the grating plane, hence allowing the diffracted light beams to scan. MEMS grating scanners have mainly been explored with the integration of electrostatic or electromagnetic actuators to achieve the out-of-plane motion. Electrostatic actuation is the most attractive actuation mechanism in the MEMS field owing to its fabrication simplicity, operating speed and power consumption. This actuation mechanism utilizes electrostatic force to drive the grating scanner when a potential difference is supplied to the device structure, such as comb drive structures or two parallel plates. For MEMS grating scanners, comb drive actuators are the most commonly adopted driving source to provide large displacement with simple structure design. This actuation method sets an original offset between the movable and fixed comb drive structures, and thus the movable fingers could be driven up and down to tilt the grating platform with a supplied voltage.

A MEMS grating scanner actuated by out-of-plane comb drive structures was successfully reported in 1997 by Kiang et al. They used typical micromachining processes to produce binary gratings on a polysilicon plate mounted on torsion bars, and electrostatic comb drive actuators were utilized to tilt the grating plate from one side. The reported device was tested in the visible range and infrared range with $1^\circ$ angular resolution and 250 resolving power, but with limited...
performance in operating speed and diffraction efficiency. Figure 2(a) shows a resonant scanning grating design based on electrostatic comb drive actuators and a movable grating. The actuators simply tilt the grating platform with an area of $2 \times 2 \text{mm}^2$ and 500 lines/mm along its central axis. The scan angle was reported to be $\pm 4^\circ$ at its resonant frequency of 500 Hz with a supplied voltage of less than 20 V, and this chip was demonstrated in a laboratory spectrometer system. Later, this scanning chip was integrated into a microspectrometer system targeting the near-infrared wavelength range. Figure 2(b) shows another typical grating scanner with improved scan angle and scan speed. The grating structure was fabricated on a single crystal silicon plate with a thickness of 75 $\mu$m, and this plate was connected to the mechanical anchors through the torsion beams and distributed springs. Several sets of comb drive actuators were designed on both sides of the plate to tilt this grating plate. The scan angle was reported to be $10^\circ$ under a resonant frequency of up to 1 kHz, thus allowing high-speed scan. It should be noted that dynamic deformation of the grating plate was controlled below 392 nm at 10$^\circ$ deflection to ensure its diffraction efficiency. This scanner architecture has been successfully demonstrated in various external-cavity quantum cascade lasers (EC-QCLs), and the diffraction efficiency of such scanners was reported to be well above 90% for the target working spectrum range, mainly the
mid-infrared wavelength range. Besides, electrostatic parallel plate structures have also been demonstrated to drive the grating plane to achieve the out-of-plane motion, as shown in Figure 3(a). The electrode was implemented below the aluminum membrane connected to the grating structure, so the grating structure could be actuated downwards with a supplied voltage.\textsuperscript{15} Such mechanism was utilized to change the distance between the grating and the target, and the actuation range was reported to be 0.54 $\mu$m under 31 V driving voltage. This device was successfully integrated into a grating interferometer system to measure the out-of-plane vibration of MEMS devices.

Electromagnetic actuation is another actuation method to achieve the out-of-plane motion by using magnetic torque to tilt the grating platform.\textsuperscript{16,17} As shown in Figure 3(b), the driving coils were implemented on the backside of the scanning grating to generate a driving force under the permanent magnet field. The blazed grating was constructed on aluminum-coated 7.9$^\circ$ off-oriented (1 1 1) silicon substrate using silicon micromachining process. The reported grating scanner resulted in a scan angle up to $\pm$ 7.15$^\circ$ at 0.35 V, and the resonant frequency was estimated to be around 560 Hz. A near-infrared spectrometer system was successfully demonstrated with diffraction efficiency over 45% in its working range of 800 to 1800 nm. Most recently, they modified the scanner using folded torsion beams with fillet corners to improve its structural reliability, which may reduce the scan angle to $\pm$ 6.1$^\circ$ at 7.63 V.\textsuperscript{18} These reported devices also indicated the potential to integrate gratings structures with typical MEMS scanning mirror. Then one can draw from the experience of these well-designed MEMS mirror scanners to construct efficient driving mechanisms for grating scanners, including electrostatic,\textsuperscript{19,20} electromagnetic,\textsuperscript{21,22} electrothermal,\textsuperscript{23,24} and piezoelectric actuation.\textsuperscript{25}

3.2. In-plane rotating MEMS scanning gratings for high-speed scanning

Instead of driving the scanners with out-of-plane motion, the diffraction grating platform can also be rotated on an axis perpendicular to the grating plane. The rotational in-plane motion can change the orientation of grating lines to drive the diffracted light beam to scan. Such in-plane motion will typically result in a bow-like scanning, which is related to the diffraction order, the incident wavelength and the grating pitch.\textsuperscript{26} However, bow-free scanning is possible when certain conditions are met.\textsuperscript{27} In this case, a subwavelength grating is commonly integrated with the in-plane driving mechanism for bow-free scanning using the first-order diffracted beam. The diffraction efficiency of subwavelength gratings can be optimized with proper design of grating profiles by using specific methods, such as rigorous coupled-wave analysis (RCWA).\textsuperscript{28} In addition, the in-plane excitation results in small dynamic deformation compared with out-of-plane motion.
excitation, so grating scanners based on in-plane motion are preferable to perform high-speed scanning with thin grating platforms. Comb drive actuator is also the dominating actuation method to realize the in-plane rotation.

Early MEMS grating scanners utilized electrostatic polysilicon micromotors to rotate the grating platform in a continuous manner. However, this type of grating scanner suffers from low scan rate and short lifetime due to the lack of an efficient bearing system and various wear issues. One possible solution is to actuate the suspended grating platform into in-plane rotational oscillation at resonance to ensure both the scan speed and the scan amplitude, and this type of scanner is called MEMS vibratory diffraction grating scanners. Figure 4(a) indicates an example of such grating scanner where the grating platform was suspended with T-shaped flexure springs. Two pairs of circular comb drive actuators were placed concentrically to rotate the central grating platform, but the achievable scan angle was quite limited for field applications. To overcome this limitation, Zhou et al. proposed a scanning grating architecture based on two identical electrostatic comb drive actuators, and these two actuators were designed to be 180° out-of-phase, shown in Figure 4(b). The T-shaped flexures were used to connect the actuators and the grating platform where the binary grating was implemented. The stress alleviation beams were designed to reduce the stress in the flexure beams, thus ensuring a large scan angle. The experiments showed that the reported grating (1 mm diameter) could achieve a scanning angle of 13.7° under a resonant frequency of 20.35 kHz for 632.8 nm wavelength laser. In addition, this study also showed an example of using the RCWA method to design the grating profile, and the achievable diffraction efficiency could be more than 80% with an optimal grating groove depth. The measured optical resolution was around 310 pixels per unidirectional scan. In Ref. [34], the operating frequency of such architecture was increased by adding more T-shaped flexures to connect the grating platform to some fixed anchors. The device was fabricated through a single mask delay etching technique, and the measured resonant frequency was 50 kHz while maintaining the scan angle at 14°. However, it is hard to guarantee the two identical comb drive actuators for driving owing to the imperfections of microfabrication technology, thus making it challenging to further improve the performance of the proposed scanning grating.

Therefore, a single circular comb drive actuator was demonstrated to drive the grating platform, as shown in Figure 5(a). The proposed device was typically a two-degree-of-freedom (2-DOF) vibration system where the circular folded beams were used to suspend the electrostatic circular comb drive actuators. T-shaped flexures were again designed to connect the grating platform and comb drive actuators, and the 1 mm diameter grating could achieve a scan angle of around 25° under a resonant frequency of 20.289 kHz. In addition, this research work also
provided a theoretical model of the proposed architecture to show its potential to scan with large amplitudes, while the developed model could accurately describe the dynamic performance of such architecture. It should be noted that these described architectures are all based on single-layered designs which fabricate the grating structures and the actuators in the same structure layer. For single-layered designs, increasing the size of the grating platform may reduce the achievable scan angle, despite a larger platform size and a larger scan angle being preferable in the field of optical scanning for better scan resolution. Thus, double-layered scanning gratings have also been explored based on the same driving mechanism, as shown in Figure 5(b). In this case, the grating platform and the actuation mechanism were fabricated separately and assembled together.\[36\] A connection hole was fabricated inside the driving platform to mount the fabricated grating using bonding glue, instead of directly fabricating the grating on the platform. The demonstrated diffraction grating was designed with a diameter of 2 mm and achieved a 33° scan angle under a resonant frequency of 23.391 kHz. The product of the scan angle and the grating diameter was measured to be 66 deg mm. With an improved micromachining process using normal bulk silicon wafers,\[37\] a flatter grating platform was achieved for better resolution. The authors reported 916 pixels per unidirectional scan in atmospheric pressure and 1460 pixels per unidirectional scan in vacuum respectively.

### 3.3. In-plane translation MEMS gratings for phase shifting

Optical phased array (OPA) is a powerful technology for steering optical beams by modulating the optical phases of each emitter in the device. OPA plays an essential role in many optical systems owing to its capability of versatile beamsteering functions, such as random-access pointing/tracking with multiple simultaneous beams.\[38\] In optical phased arrays, the optical beam is steered by creating a linear phase ramp across the incident aperture.\[39\] The most common type of OPA is built on liquid crystals with limited performance in response time and steering efficiency at large angles.\[40\] Thus, MEMS OPA device has received increasing research interest with the aim of overcoming the limitation of liquid crystal OPAs. It is expected to provide outstanding properties in power consumption, cost, and device weight. It should be noted that a large phase shift is always preferred to allow wide steering angles, which can be realized by dividing the linear phase into smaller phase ramps with modulo-2π resets. A “folded” phase profile is thus generated to represent a blazed grating, and such beamsteering system is very wavelength-dependent (dispersive).
Till now, MEMS mirror arrays have seen major applications in the construction of OPA devices where a phase shift is created between the mirror elements. Two types of driving motion have been utilized to achieve such phase shift, including the piston motion (vertical driving) and the tilt of the MEMS mirrors. The combination of these two driving motions has also been explored to provide efficient steering over wide angles, known as tip/tilt and piston (TTP) micromirrors. A variety of TTP micromirrors have been demonstrated using different actuation mechanisms, mainly by electrostatic actuation and electrothermal actuation. Figure 6(a) indicates an example of a TTP mirror element in a 4 x 4 array, where each mirror was driven by an electrothermal actuator resulting in a ± 30° tilt angle and a 215 μm displacement with driving voltages of 5 Vdc and 4 Vdc respectively. The response of such micromirrors was estimated to be 10 ms. For MEMS mirror-based OPAs, the fill factor is a limiting factor which can be improved with hidden actuator design, but the fabrication of such actuator may require specific assembling and bonding process, limiting the array size. In addition, high reflectivity is typically required for MEMS mirror arrays in high power systems, and thus high contrast grating (HCG) structures provide a possible solution for this limitation. The HCG is a sub-wavelength grating structure built on a thin device layer without metal coating. Chang-Hasnain et al. have given a detailed theoretical and experimental study on HCG structures whose reflectivity and reflection spectrum can be changed through the modulation of grating thickness, grating pitch, and grating bar width. Figure 6(b) shows an example of an OPA based on HCG fabricated with single crystal silicon for wide applicability to handle high powers. The experiments reported a 1.2° beamsteering angle for the 1550 nm laser light source, and the reflectivity of such device reached 99%. However, the large anchor structures typically limit the fill factor of the reported device to 36%. Later, they demonstrated a 32 x 32 OPA device with similar architecture and improved the fill factor to 85% using hidden actuators design. The OPA has a total aperture of 702 x 702 μm², and the maximum steering angle was measured to be ± 2°. In addition, the resonant frequency reached up to 0.4 MHz, corresponding to a response time of 3.8 μs, because of the usage of light HCG structures. Similar architectures can also be found in high-speed beamsteering systems.

As described, the phase of reflected light from a mirror is typically dependent on the incident wavelength that makes MEMS mirror-based OPAs dispersive, limiting their uses to narrowband applications. Thus, nondispersive OPAs have also been demonstrated by executing in-plane translation motions to an array of micro-gratings, as shown in Figure 7(a). The array of grating elements was initially aligned collinearly to act as a single grating, while the electrostatic comb drive actuators were designed to provide the in-plane translation motion for each grating element. For the first-order diffracted beam, a phase shift could be generated...
on each grating element. In this way, the phase shift is mainly determined by the ratio of the in-plane displacement to the grating pitch and is independent of the wavelength, so such a design is nondispersive for broader band applications. The fill factor of the device was about 72\%, and the resonant frequency of the designed grating element was reported to be 6.3 kHz for high-speed switching. In addition, a 180° phase difference could be achieved with an in-plane displacement of 3.8 μm, and the experiments also proved that the proposed mechanism was nondispersive with the potential for broadband applications. Later, this concept was extended to construct a large 2D array consisting of 160 × 160 phase shifters.\[59\] Figure 7(b) indicates the proposed OPA device with an aperture of 3.1 mm × 3.2 mm. As shown, the fabricated grating element was mounted on the folded beam springs of the hidden comb drive actuators, thus improving the fill factor to 87.7\%. With well-designed grating structures, the demonstrated device resulted in an optical efficiency of 85\% in the near-infrared telecom wavelength range, a field of view of 6.6° × 4.4° at 1550 nm wavelength, and a resonant frequency of 55 kHz corresponding to a response time of 5.7 μs. Besides, a 180° phase difference was achieved with a displacement of ± 0.5 μm under a 10.5 V driving voltage.

We have reviewed several MEMS grating devices actuated with three different motion types. MEMS actuators have been widely employed to actuate a grating platform for out-of-plane motion, and thus functional one-dimensional scan can be achieved to construct various spectroscopic systems and scanning systems. However, the out-of-plane MEMS scanning grating is usually designed with limited operating frequency to control the dynamic deformation that will affect the optical performance of grating devices. The in-plane motion-based MEMS scanning gratings can be operated at higher frequency for high-speed scanning applications, but it should be noted that certain conditions should be satisfied to achieve bow-free scanning. In addition, MEMS gratings devices actuated with the in-plane translation can generate phase shifts between the grating elements with high operating frequency, and such grating devices can be used in OPA systems for beamsteering applications.

### 3.4. Applications of MEMS scanning gratings

The integration of MEMS actuators and grating structures allows the incident light on the grating structures to scan along a target trajectory. Thus, MEMS scanning gratings can be used in the same way as MEMS scanning mirrors in various scanning systems for monochromatic applications,
such as laser projection displays systems, single-pixel imaging systems, laser scanning confocal microscopes and many other applications.\(^{[60-63]}\) Light Detection and Ranging (LiDAR) is a special scanning system to measure the dynamic distance, and such systems can be constructed with either MEMS scanners or MEMS OPA devices. Figure 8 depicts a typical LiDAR system using a MEMS device, and a short laser pulse is generated by the transmitter. The MEMS device can steer the light to scan across the target along the designed scanning trajectory. Then the distance can be calculated by determining the costing time from the input pulse to the detected pulse. Such architectures have been demonstrated to build high-resolution and accurate measuring systems.\(^{[64,65]}\) MEMS OPA devices have become a common solution in LiDAR systems, owing to their good performance in stabilization, random-access pointing/tracking, power handling, efficiency, and steering speed. Besides, MEMS OPA devices can achieve steering of both azimuth and elevation on one surface compared with other OPA devices.\(^{[66]}\) It should be noted that this type of OPA device provides a potential solution to establish compact LiDAR systems which are highly required in intelligent vehicles.\(^{[67,68]}\) In addition, MEMS OPA devices also have applications in other fields, such as optical communications,\(^{[69]}\) holographic displays,\(^{[70]}\) and three-dimensional imaging.\(^{[71]}\)

It should be noted that the dispersive properties of gratings make grating scanners attractive in wavelength dependent applications, thus MEMS grating scanners, particular out-of-plane MEMS scanning gratings, see most of their applications in the construction of compact spectrometer systems. The Czerny-Turner configuration, shown in Figure 9(a), provides a possible solution to build a compact spectrometer by using the grating to disperse the incoming light, while a detector array can be placed at the focal plane of the focusing mirror to measure the dispersed light intensities. However, detector arrays are costly or unavailable for some wavelengths. MEMS grating scanners can focus different wavelengths sequentially onto a single-pixel detector through dynamic scanning, thus benefiting from single-pixel detector technology.\(^{[73]}\) The resolution of such spectrometers is dependent on the slit width and the reciprocal dispersion of the diffraction grating. In addition, the signal-to-noise ratio (SNR) is affected by the input light energy and the properties of the applied detectors. One possible way to improve the SNR is to increase the number of co-added scans to average the intra-spectral noise.\(^{[74,75]}\)

Till now, various spectrometers have been reported with the Czerny-Turner configuration for the visible range\(^{[76]}\) and near-infrared range (NIR).\(^{[74,77,78]}\) The resulted resolution of these reported NIR spectrometers was reported to be about 10 nm and the scanning speed was measured to be several milliseconds. A mid-infrared spectrometer has also been reported using a modified Czerny-Turner monochromator layout.\(^{[79]}\) The proposed spectrometer was reported to
work at a wavelength range of 3968 nm–4520 nm with a measured resolution of 15 nm, and it was successfully applied to sense dissolved carbon dioxide in aqueous solutions. In addition, the size of the spectrometer can be shrunk further with modified spectrometer configurations, and one example is given in Ref. [80]. The reported device was designed with a compact size of 9.6 mm × 5.3 mm × 0.5 mm to indicate its potential to be integrated within flat mobile phones. Figure 9(b) shows an example of an asymmetrical crossed Czerny-Turner system, which could broaden the spectral range of the resulted device. The crossing of light was beneficial to reduce the volume of the instrument, while the coma aberration was eliminated at specified wavelength by designing the focusing mirror and the collimation mirror with different focal lengths. The modified design could improve the SNR up to 281:1 for wavelengths ranging from 800 to 2500 nm. The reported resolution was 10 nm and 15 nm for the 800–1650 nm and 1650–2500 nm wavelength ranges respectively, and the scan time was measured to be 1.8 ms.

Hyperspectral imaging capable of obtaining a continuous spectrum at each pixel has gained increasing attention in recent years. A hyperspectral camera can capture an image of an object as well as identify the material of the object. MEMS grating scanners have been explored in this field owing to its scanning and dispersion properties. In Ref. [82], a typical NIR hyperspectral imager was reported by using a moving slit to scan across the target, and the MEMS grating scanner was rotated to scan across the slit. The grating scanner also dispersed the incident light from the slit onto a detector array to capture the spectral information of the slit. A 3D hyperspectral data cube of the target could be obtained by moving the entrance slit. Vibratory in-plane grating scanner has also been employed to construct a hyperspectral imager, whose working principle is schematically shown in Figure 10. Imagine that a MEMS grating is illuminated with a broadband light source. The grating dispersed the incident light, and the dispersed light was directed onto a screen by a mirror. Then, light at different wavelengths could be driven to scan different lines by rotating the in-plane MEMS grating scanner. With this principle, a hyperspectral imager could be built by reversing the ray direction and replacing the light source with a single-pixel detector. A slit was used to replace the screen to limit the field of view of the fore optics to a straight line. The intensity distribution along the slit could be simply captured by in-plane rotation of the MEMS grating, while the dynamic rotation of the mirror allows different wavelengths into the opening slit. This concept could be used to build a spectral line imager. Thus, the hyperspectral image of the target could be obtained by moving the entrance slit across the target to achieve pushbroom scanning. The proposed structure based on two MEMS actuators can ensure the high-speed scanning for field applications. In addition, Du et al. proposed a mathematical way to determine the instantaneous field of view that can be captured by the detector in an instant of time during the scanning process and the corrected distance to make such hyperspectral imager capable for real applications.
Diffraction grating integrated with MEMS technology also provides an efficient way to build various MEMS sensors. Two types of MEMS sensors have been explored using MEMS diffraction grating. The first type is based on the fact that the change of MEMS grating periodic structures can modulate their diffraction properties, so capturing the diffracted intensities can be used to sense the source that causes the change in the MEMS grating structure. Another type of MEMS sensor is constructed on a compact interferometer system, where MEMS diffraction grating is suspended to diffract part of the incident light. While the remaining part passes through the grating and is reflected back to the grating to interfere with the diffracted light. The interfering intensity can be changed by varying the distance between the grating and the reflector, so the architecture provides an efficient method to sense the varying distance with nanometer precision. By now, these two MEMS architectures have been widely been demonstrated for different sensing applications, including the accelerometer,[86–88] position sensor,[89,90] acoustic sensor,[91] out-of-plane measurement and in-plane measurements.[92,93]

4. MEMS tunable grating architecture

The tunable grating device is another important research topic in the field of optical MEMS. MEMS tunable gratings are generally constructed with various MEMS actuators to change the shape of grating structures, thus modulating the light diffraction properties of resulted devices. This type of tunable device is preferable in applications where tunable diffraction angles, efficiency or wavelengths are required. Much research effort has been made on the construction of tunable gratings using a variety of feature designs and MEMS actuators. In this field, the achievable tunable range and grating efficiency are commonly used to evaluate the performance of the resulted tunable gratings, and a larger tuning range is desirable to broaden their applications. However, it might be hard to keep the grating efficiency of tunable gratings constant during the modulation process, as the shape modulation can dynamically change the duty cycle of grating structures, especially for pitch-tunable gratings. MEMS tunable grating devices can be divided into two types according to the applied tuning methods, namely profile-tuning gratings and pitch-tuning gratings. The following part is going to give a detailed introduction on these two types of tunable gratings in terms of their typical architectures, advantages and limitations.

4.1. MEMS gratings with tunable profile

The surface profile of a grating within one period can be changed using MEMS actuators, thereby varying the grating’s diffraction efficiency and redistributing light energy among different diffraction orders. These MEMS grating with tunable grating profiles can be used in various light
modulation and sensing applications. In the field of MEMS gratings with variable profile, vertical tuning is often used, such as the grating light valve (GLV) device\,[94,95] The electrostatic actuation is the most commonly adopted actuation method to construct a GLV device where each reflective beam, also called “ribbon”, is suspended over its underlying electrode with a small air gap, as depicted in Figure 11(a). All movable ribbons reflect the incident light at the initial state, while alternating ribbons can be pulled down through electrostatic force with a moving distance of approximately one-quarter wavelength to generate diffraction effect on the incident light. Thus, GLV devices achieve two different modulation states to commonly serve as the light modulator, and the performance of such devices is primarily dependent on the design of ribbon structures, such as its length, width and shape.\,[97,98] The movable ribbon may not maintain its flat profile due to the bending of reflective ribbons during the modulation process, hence significantly affecting the grating efficiency. Then some research works have been conducted to optimize the beam parameters to reduce this effect induced by the non-flat deflection,\,[99,100] and the shape of the beam could also be modified to achieve better tuning behavior.\,[101] Figure 11(b) indicates a novel device design where the micromirrors are suspended with soft flexures that can be pulled towards the substrate when a voltage is supplied to the flexures and the underlying electrode.\,[96] With the linkage arm, the mechanical coupling between the mirror and the flexures could change the tuning behavior of micromirrors in traditional GLV devices to avoid the micromirror bending during the actuation process. The reported device was designed with 700 μm length and 50 μm width, and the results showed negligible crosstalk and bowing to be 0.14 μm over the total length. The GLV device has also been fabricated with other materials, such as poly-SiGe, by taking advantage of CMOS-integrated MEMS technology.\,[102] Such GLV device could achieve good tuning behavior under a 16 V driving voltage, and the resonant frequency was reported to be 90 kHz for the ribbon with 50 μm width. In Ref.\,[103,104], the GLV device was constructed with dielectric film with high permittivity and a field-controlled air gap to reduce the required driving voltage.

![Figure 12](imageURL)
In addition, piezoelectric actuation has also been employed to build the GLV device,\textsuperscript{105} as shown in Figure 12(a). The bridge structures were connected to the thin PZT film to work as the reflective ribbons. With the supplied voltage, the PZT film would shrink horizontally to drive the connected bridge structures to move in the vertical direction. The substrate of this reported device also reflects the incident light, and the piezoelectric actuation modulates the height between the top mirror and the substrate to obtain the dynamic phase shift modulation. The device resulted in a 400 nm tuning range within 10 V, and it could be operated at a frequency up to 500 kHz. Besides, they also introduced a compact light modulator with a size of $13.4 \times 12.0 \times 11.0$ mm$^3$ suitable for mobile laser projection display applications. This tuning principle has also seen its application in the polychromator that modulates diffraction efficiency by controlling the beam height.\textsuperscript{108} The tunable profile can also be realized by changing the blaze angle of tunable blazed gratings (TBG). The TBG is generally constructed with a series of grating beams where one end is fixed to the anchor, while the other end of the grating beams can be deflected using MEMS actuators to modulate the blaze angle.\textsuperscript{109} The electrostatic and thermal actuators have been reported to change the blaze angle by tilting a series of suspension grating beams.\textsuperscript{110} The achievable tuning angles were reported to be 1.25$^\circ$ and 0.86$^\circ$ for the electrostatic and thermal actuator, respectively. MEMS OPA device can be regarded as a blazed grating with tunable blaze angle by creating periodic structures within the device array.\textsuperscript{111} However, the achievable tuning blaze angles for these designs are still quite limited. Thus, Yu et al. proposed modified designs with enlarged dimple structures where the dimple structure was designed to be 1.75 μm for the standard 2.0 μm air spacing, and this structure could support the rotation of grating beams when its bottom lands on the substrate under an applied voltage.\textsuperscript{112,113} The maximum tuning angle was measured to be 5.19$^\circ$ with 97 V pull-in voltage. However, the usage of two-layer polysilicon surface micromachining process limits the diffraction efficiency of the resulted tunable gratings.

MEMS gratings with tunable profile are also employed to construct grating interferometer for sensing applications. Figure 12(b) shows a typical interferometer design consisting of an array of interdigitated fingers that are alternately connected to the movable part and support substrate.\textsuperscript{106} When a light beam is directed on the array of interdigitated fingers, the diffracted intensities are dependent on the out-of-plane offset between the fixed set of fingers and movable fingers. The interferometer was first utilized to measure the deflection of atomic force microscope cantilevers with simple alignment procedure.\textsuperscript{114–116} Later, this concept was extended to build the accelerometer for nano-g precision.\textsuperscript{117–119} Figure 12(c) shows a novel lamellar grating with tunable profile design for Fourier-transform spectrometer (FTS).\textsuperscript{107} The driving coils were positioned under the device, while a permanent magnet was set perpendicular to the illustrated central platform. Thus, the generated electromagnetic force could actuate the movable surface of the lamellar grating up and down. This device avoided pull-in instability to allow larger out-of-plane deflections with increasing applied current, and the experimental results indicated a deflection of 125 μm with 129 mA-amplitude currents. In the reported FTS system, the spectral resolution was measured to be 3.8 nm at 632.8 nm and 3.44 nm at 532 nm.

4.2. MEMS gratings with tunable pitch

In contrast to vertical tuning to modify the grating profile within a period, the transverse tuning method modulates the grating pitch in a continuous manner to achieve fine tuning. Three MEMS actuation mechanisms have been utilized for the construction of MEMS tunable grating devices, including electrostatic, piezoelectric and thermal actuation. The typical structures for this tunable grating consist of an array of parallel reflective grating grooves suspended by spring flexures. Thus, the grating array can be evenly spread out to change the grating pitch with specific MEMS actuators. Figure 13(a) indicates a tunable grating design based on piezoelectric actuation,
and the grating grooves were implemented on a piezoelectric membrane that could deform its shape with an applied voltage. It can be seen that both ends were connected to the piezoelectric actuators that could provide sufficient force to strain the membrane by taking advantage of the piezoelectric effect of the PZT material. The achievable angular range was reported to be about 400 μrad with 0.21% strain for the first order diffraction, corresponding to an 8 nm change in the grating periodicity when 10 V voltage was supplied to the actuators. It can be seen that the changing rate of period is quite limited and restricts its applications, but this actuation method is suitable for applications where precise actuation is required with nanometer resolution.

The electrostatic comb drive actuation sees major applications in the field of MEMS pitch-tunable grating, and Figure 13(b) depicts a typical example of such grating device. It can be seen that the series of reflective grating beams were suspended with the holding springs connected to the actuation springs. Additionally, the actuation springs were connected to the comb drive finger structure as well as the anchors. Therefore, the grating pitch could be changed through mechanical stretching when a voltage was supplied to the comb drive actuator. The proposed device was built through an easy single-mask fabrication process, and the resulted device achieved an angular tuning range of 250 μrad with 1 μrad resolution under 10 V driving voltage. The pitch change was reported to be 57.4 nm, corresponding to a 0.47% changing rate in grating period. Similar architecture can be also found in Ref. with improved period tunability of 2.5% and an expected resonant frequency at 28.5 kHz. Later, this architecture was applied to construct a

Figure 13. Schematic showing the working principle of pitch-tunable grating (a) with piezoelectric actuation; (b) with electrostatic comb drive actuation.

Figure 14. Mechanical structures of pitch-tunable grating (a) with tilted beams to improve the tuning range; (b) with MEMS thermal expansion beam actuation.
MEMS pitch-tunable grating that could work in reflective or transmissive mode by incorporating silicon-on-glass technology.\cite{124} The reported device could achieve a 4.62% changing rate in grating period with 65 V supplied voltage. After tilted supporting beams was found to have larger travel range for electrostatic comb actuators,\cite{125} pitch-tunable gratings based on the tilted beams have been demonstrated with improved changing rate in grating period,\cite{126} and Figure 14\( (a) \) shows the architecture of such design. The array of grating beams was connected to the folded supporting beam with a tilt angle, and the tilted beams were connected to the comb drive actuators for driving. The proposed tilted beam design improved the changing ratio to 10.34%. More recently, a suspended serpentine is employed as the grating structures that could be tuned through the comb drive actuators in a similar way, which was reported to be suitable for spaceborne applications.\cite{128} The application of electrostatic actuation in constructing MEMS tunable gratings can also be found in Ref. [129,130]. All demonstrations showed limited tuning range owing to the pull-in instability of electrostatic actuators,\cite{131} and the maximum tuning range has been reported to be 12.5% using electrostatic actuators.\cite{132}

To overcome the limited tuning range, MEMS thermal actuators have also been employed to stretch the grating beams structures by taking advantage of thermal expansion of the MEMS beams. For example, in Ref. [133] the rhomboid heat actuators were utilized to tune the grating pitch of the MEMS grating, and the resulted grating device was demonstrated as an add/drop multiplexer to show the 40% changing rate in grating pitch. Figure 14\( (b) \) shows another example of tunable grating\cite{127} where the thermal actuators were designed with the expansion beam responding to temperature variation, and the expansion beams were connected to the lever that could amplify the displacement provided by the expansion beam. The amplified displacement was guided by the guiding spring set to stretch the parallel reflective slats that were suspended with spring flexures. The reported device achieved a 300 μm tuning displacement with 19 V supplied voltage, which indicated a changing rate of up to 30% in grating period. However, this thermal actuation method typically requires long modulation time and high power consumption, thus limiting its applications. In addition, the grating beams could also be coated with magnetic materials, so inter-nanomagnet forces could be generated to slightly deform the free standing beams or clump together under the influence of an external magnet field. Thus, this type of device can modulate the grating pitch in a continuous manner or in a digital manner.\cite{134}

The blazed grating has also been used for the construction of pitch-tunable grating. In this case, the blazed grating is fabricated as a series of reflective parallel beams, so the reported pitch-
tunable architectures can also be employed to strain the grating beams with blazed grating profiles. It is also noted that some research work employ multi-level grating structures to approximate the continuous blazed profiles to avoid the potential difficulty of forming an optically smooth blazed surface profile. Then, a four-level grating structure was utilized to build the pitch-tunable blazed grating,\cite{135,136} as shown in Figure 15(a). A series of freestanding four-level blazed grating beams were connected together though finger springs. Anchors were utilized to suspend the blazed grating beams, and electrostatic comb drive actuators were chosen as the driving source to stretch the whole structure to modulate the grating pitch. The reported device was fabricated through a two-mask process and achieved roughly a 15 μm tuning range with a 100 V supplied voltage, corresponding to 5.4% tuning ratio in grating period. In addition, Yang et al. reported a grating architecture that combines the modulation of blaze angles and grating periods, and the schematic of the proposed device is depicted in Figure 15(b)\cite{137}. As shown, the reflective grating slats were connected to the actuators through the holding springs, thus allowing the modulation of grating periods. Only one end of each slat was connected to the holding springs, so the free end could be pulled down when a voltage was supplied between the slat and its underlying electrodes with designed L-shaped dimples. The test results indicated the device could achieve a period tuning range of one-tenth of the grating pitch and tunable blaze angle up to 2.08°. However, the construction of such devices is quite complicated due to the combination of surface micromachining and bulk micromachining process.

In recent years, tunable gratings have also been constructed on flexible and deformable substrates with embedded grating lines for better tuning behaviors, such as dielectric elastomer.\cite{138,139} Other tunable gratings can also be found in shape memory alloy and graphene structures\cite{140–142} with large tuning range. Even though non-MEMS actuation methods result in a larger tuning range, the power consumption is much higher than that of MEMS tunable gratings. Thus, MEMS tunable grating is an attractive technology in applications where lower power consumption is required.

### 4.3. Applications of MEMS tunable gratings

Considering that GLV devices provide a competitive edge over traditional light modulators in terms of switching time, low loss and simplicity in fabrication, GLV devices have been utilized as a functional light modulator for various applications.\cite{143–145} In addition, GLV devices can be employed as high-speed optical switches for optical communication applications owing to its modulation properties.\cite{146–148} Besides the described sensor applications,\cite{149} MEMS tunable gratings have also been applied to construct microspectrometers, since they can select specific wavelengths sequentially onto the detector by varying the diffraction properties. For microspectrometers based on pitch-tunable gratings, fine scan can be achieved across the target spectrum, but their performance is limited by the changing diffraction efficiency and the tuning range provided by the MEMS actuators.\cite{150} MEMS gratings with tunable profile provide another solution to build compact spectroscopic systems. Till now, several spectroscopic systems have been demonstrated that mainly cover the near-infrared range and mid-infrared range.\cite{151–153}

A tunable single-wavelength laser capable of producing narrow linewidth and continuously tuning laser is required in many field applications, such as spectroscopy. The integration of MEMS external cavity with a light source, such as solitary diode laser, can be employed to generate continuous laser outputs with narrow linewidth. Therefore, tunable gratings have also seen applications in the development of MEMS external cavity where MEMS tunable gratings are used as filters to select a single wavelength laser with narrow linewidth for output.\cite{154–156} These MEMS tunable lasers get outstanding performance in fine tuning, operating speed, device size and power consumption. In addition, MEMS gratings with tunable profile have also been developed as polychromators to generate synthetic spectra.\cite{108} By modulating the relative height
of the grating microbeams, different diffraction effects can be generated to produce any desired spectra which play a crucial role in correlation spectroscopy. The use of “leveraged bending” and “strain-stiffening” methods allow large displacement of this type of polychromator without suffering from non-flat deflection, thus this polychromator can be applied in the mid-infrared range.\textsuperscript{[157]} Such device has also been successfully integrated with a sensing satellite to detect the spectra of the moon surface.\textsuperscript{[158]}

5. Conclusion

In this paper, we reviewed two main grating structures integrated with MEMS technology. The first grating structure employs MEMS actuators to achieve functional optical scan, while the second utilizes MEMS actuators to modulate the diffraction efficiency in a dynamic process. For the first type of MEMS grating, three motion types have been explored to achieve the target scan. It can be seen that the out-of-plane motion type has limited scan angle owing to the limited displacement provided by the electrostatic actuators. The operating frequency of out-of-plane MEMS scanning gratings is limited, considering that this type of motion will result in larger dynamic deformation under high-speed scanning that degrades its system performance. For in-plane motion-based scanning gratings, the dynamic deformation can be controlled to ensure its performance for high-speed scanning, and thus larger scan angle can be obtained under resonant operation. The in-plane translation of MEMS grating is mainly used in OPA systems to make such systems nondispersive for boarder applications compared with traditional MEMS mirror-based OPA devices.

For MEMS gratings with tunable profiles, the GLV device can achieve high-speed modulation with proper design, but its non-flat deflection should be highlighted for its effect on system performance. GLV devices get wide applications in various display and scanning systems. Besides, the tunable grating profiles can change the diffraction properties of MEMS gratings to make them attractive in the construction of various spectrometers and MEMS sensors. MEMS pitch-tunable grating has limited tuning range compared with non-MEMS tunable grating, thus limiting its applications. However, MEMS tunable grating seems to be the better choice in applications requiring low power consumption. In addition, MEMS scanning gratings are typically built with fixed grating structures which can be properly designed for high diffraction efficiency at certain wavelength range, while the diffraction efficiency of MEMS tunable gratings cannot be maintained owing to the changing grating structures, which is also another limitation of such grating architecture for some field applications. In terms of applications, both types of MEMS gratings can be used in scanning systems and wavelength sensing applications. It should be noted that MEMS OPA devices offer an efficient solution for light detection, considering the increasing requirement for light sensing in intelligent vehicles.

Overall, MEMS grating scanners, owing to the miniaturization ability of MEMS technology, is widely expected to provide an efficient way to construct compact scanners, spectral sensing devices and light detection systems in the future, while tunable gratings have the potential for high-speed scanning and display systems, compact MEMS sensors, and high-resolution spectroscopic systems.

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References

[1] Holmström, S.T.S.; Baran, U.; Urey, H. MEMS laser scanners: A review. J. Microelectromech. Syst. 2014, 23, 259–275. DOI: 10.1109/JMEMS.2013.2295470.

[2] Sun, J.; Guo, S.; Wu, L.; Liu, L.; Choe, S.W.; Sorg, B.S.; Xie, H. 3D in vivo optical coherence tomography based on a low-voltage, large-scan-range 2D mems mirror. Opt. Express. 2010, 18, 12065–12075. DOI: 10.1364/OE.18.012065.

[3] McManamon, P.F. 2005 An overview of optical phased array technology and status. Liquid Crystals Optics Appl. 5947, 59470L. DOI: 10.1117/12.631412.

[4] McManamon, P.F.; Bos, P.J.; Escuti, M.J.; Heikenfeld, J.; Serati, S.; Xie, H.; Watson, E.A. A review of phased array steering for narrowband electrooptical systems. Proc. IEEE 2009, 97, 1078–1096. DOI: 10.1109/JPROC.2009.2017218.

[5] Liu, A.Q.; Zhang, X.M. A review of MEMS external-cavity tunable lasers. J. Micromech. Microeng. 2007, 17, R1–R13. DOI: 10.1088/0960-1317/17/1/R01. DOI: 10.1088/0960-1317/17/1/R01.

[6] Liu, A.Q.; Zhang, X.M. A review of MEMS external-cavity tunable lasers. J. Micromech. Microeng. 2007, 17, R1–R13. DOI: 10.1088/0960-1317/17/1/R01. DOI: 10.1088/0960-1317/17/1/R01.

[7] Grahmann, J.; Merten, A.; Herrmann, A.; Ostendorf, R.; Drabe, C.; Kamenz, J. Large MOEMS diffraction grating results providing an EC-QCL wavelength scan of 20%. In Proceedings of the SPIE 9375, MOEMS and Miniaturized Systems XIV, San Francisco, California, 2015; p. 93750W. DOI: 10.1117/12.2209064.

[8] Butschek, L.; Hugger, S.; Jarvis, J. Microoptoelectromechanical systems-based external cavity quantum cascade lasers (ec-qcl): An application field for moems based scanning gratings. In Proceedings Volume 8977, MOEMS and Miniaturized Systems XIII. San Francisco, California, 2014; p. 897708. DOI: 10.1117/12.2039950.

[9] Grahmann, J.; Merten, A.; Ostendorf, R.; Fontenot, M.; Bleh, D.; Schenck, H.; Wagner, H.J. Tunable external cavity quantum cascade lasers (ec-qcl): An application field for moems based scanning gratings. In Proceedings Volume 8977, MOEMS and Miniaturized Systems XIII. San Francisco, California, 2014; p. 897708. DOI: 10.1117/12.2039950.

[10] Sun, J.; Guo, S.; Wu, L.; Liu, L.; Choe, S.W.; Sorg, B.S.; Xie, H. 3D in vivo optical coherence tomography based on a low-voltage, large-scan-range 2D mems mirror. Opt. Express. 2010, 18, 12065–12075. DOI: 10.1364/OE.18.012065.

[11] Butschek, L.; Hugger, S.; Jarvis, J. Microoptoelectromechanical systems-based external cavity quantum cascade lasers for real-time spectroscopy. Opt. Eng. 2017, 57, 1. DOI: 10.1117/1.OE.57.1.011010.

[12] Kim, B.; Degertekin, F.L.; Kurfess, T.R. A micromachined scanning grating interferometer for the out-of-plane vibration measurement of Mems. J. Micromech. Microeng. 2007, 17, 1888–1898. DOI: 10.1088/0960-1317/17/9/018.

[13] Zhou, Y.; Wen, Q.; Wen, Z.; Yang, T. Modeling of MOEMS electromagnetic scanning grating mirror for NIR microspectrometer. AIP Adv. 2016, 6, 025025. DOI: 10.1063/1.4942973.

[14] Zhou, Y.; Wen, Q.; Wen, Z.; Huang, J.; Chang, F. An electromagnetic scanning mirror integrated with blazed grating and angle sensor for a near infrared micro-spectrometer. J. Micromech. Microeng. 2017, 27, 125009. DOI: 10.1088/1361-6439/aa85ed.

[15] Chen, L.; Gu, W.; Wen, Q.; Li, D.; Lei, H.; Huang, J. Highly reliable electromagnetic MOEMS scanning grating mirror based on folded torsion beam with fillet corners. Mod. Phys. Lett. B. 2020, 34, 2050343. DOI: 10.1142/S0217732320503431.

[16] Aguirre, A.D.; Hertz, P.R.; Chen, Y.; Fujimoto, J.G.; Piyawattanametha, W.; Fan, L.; Wu, M.C. Two-axis mems scanning catheter for ultrahigh resolution three-dimensional and en face imaging. Opt. Express. 2007, 15, 2445–2453. DOI: 10.1364/OE.15.002445.

[17] Liu, J.T.; Mantella, M.J.; Ra, H.; Wong, L.K.; Solgaard, O.; Kino, G.S.; Piyawattanametha, W.; Contag, C.H.; Wang, T.D. Miniature near-infrared dual-axes confocal microscope utilizing a two-dimensional microelectromechanical systems scanner. Opt. Lett. 2007, 32, 256–258. DOI: 10.1364/OL.32.000256.
Yalcinkaya, A.D.; Urey, H.; Brown, D.; Montague, T.; Sprague, R. Two-axis electromagnetic microscanner for high resolution displays. *J. Microelectromech. Syst.* **2006**, *15*, 786–794. DOI: 10.1109/JMEMS.2006.879380.

Kim, K.H.; Park, B.H.; Maguluri, G.N.; Lee, T.W.; Rogomenti, F.J.; Bancu, M.G.; Bouma, B.E.; de Boer, J.F.; Bernstein, J.J. Two-axis magnetically-driven mems scanning catheter for endoscopic high-speed optical coherence tomography. *Opt. Express.* **2007**, *15*, 18130–18140. DOI: 10.1364/OE.15.018130.

Xie, H.; Pan, Y.; Fedder, G.K. Endoscopic optical coherence tomographic imaging with a Cmos-mems micromirror. *Sens. Actuat. A Phys.* **2003**, *103*, 237–241. DOI: 10.1016/S0924-4247(02)00347-3.

Jain, A.; Kopa, A.; Pan, Y.; Fedder, G.K.; Xie, H. A two-axis electrothermal micromirror for endoscopic optical coherence tomography. *IEEE J. Select. Topics Quantum Electron.* **2004**, *10*, 636–642. DOI: 10.1109/JSTQE.2004.829194.

Koh, K.H.; Kobayashi, T.; Lee, C. A 2-D MEMS scanning mirror based on dynamic mixed mode excitation of a piezoelectric PZT thin film S-shaped actuator. *Opt. Express* **2011**, *19*, 13812–13824. DOI: 10.1364/OE.19.013812.

Beiser, L. Holographic scan with geometric and interferometric zone plates: a clarification. *Appl. Opt.* **1983**, *22*, 1614–1615. DOI: 10.1364/AO.22.001614.

Ono, Y.; Nishida, N. Holographic disk scanners for bow-free scanning. *Appl. Opt.* **1983**, *22*, 2132–2136. DOI: 10.1364/AO.22.002132.

Moharam, M.G.; Gaylord, T.K. Rigorous coupled-wave analysis of planar-grating diffraction. *J. Opt. Soc. Am.* **1981**, *71*, 811–818. DOI: 10.1364/JOSA.71.000811.

Hart, M.R.; Conant, R.A.; Lau, K.Y.; Muller, R.S. Stroboscopic interferometer system for dynamic MEMS characterization. *J. Microelectromech. Syst.* **2000**, *9*, 409–418. DOI: 10.1109/84.896761.

Smith, S.W.; Yasseen, A.A.; Mehregany, M.; Merat, F.L. Micromotor grating optical switch. *Opt. Lett.* **1995**, *20*, 1734–1736. DOI: 10.1364/OL.20.001734.

Zhou, G.; Logeeswaran, V.J.; Chau, F.S.; Tay, F.E.H. Micromachined in-plane vibrating diffraction grating laser scanner. *IEEE Photon. Technol. Lett.* **2004**, *16*, 2293–2295. DOI: 10.1109/LPT.2004.834847.

Tang, W.C.; Nguyen, T.C.H.; Judy, M.W.; Howe, R.T. Electrostatic-comb drive of lateral polysilicon resonators. *Sens. Actuators A Phys.* **1990**, *21*, 328–331. DOI: 10.1016/0924-4247(90)85065-C.

Zhou, G.; Du, Y.; Zhang, Q.; Feng, H.; Chau, F.S. High-speed, high-optical-efficiency laser scanning using a MEMS-based in-plane vibratory sub-wavelength diffraction grating. *J. Micro mech. Microeng.* **2008**, *18*, 085013. DOI: 10.1088/0960-1317/18/8/085013.

Du, Y.; Zhou, G.; Cheo, K.K.L.; Zhang, Q.; Feng, H.; Chau, F.S. A high-speed MEMS grating laser scanner with a backside thinned grating platform fabricated using a single mask delay etching technique. *J. Micro mech. Microeng.* **2010**, *20*, 115028. DOI: 10.1088/0960-1317/20/11/115028.

Du, Y.; Zhou, G.Y.; Cheo, K.K.L.; Zhang, Q.X.; Feng, H.H.; Chau, F.S. A 2-DOF circular-resonator-driven in-plane vibratory grating laser scanner. *J. Microelectromech. Syst.* **2009**, *18*, 892–904. DOI: 10.1109/JMEMS.2009.2023844.

Du, Y.; Zhou, G.Y.; Cheo, K.K.L.; Zhang, Q.X.; Feng, H.H.; Chau, F.S. Double-layered vibratory grating scanner for high-speed high resolution scanning. *J. Microelectromech. Syst.* **2010**, *19*, 1186–1196. DOI: 10.1109/JMEMS.2010.2067440.

Du, Y.; Zhou, G.; Cheo, K.K.L.; Zhang, Q.; Feng, H.; Chau, F.S. A 21.5kHz high optical resolution electrostatic double-layered vibratory grating laser scanner. *Sens. Actuat. A Phys.* **2011**, *168*, 253–261. DOI: 10.1016/j.sna.2011.04.007.

McManamon, P.F.; Dorschner, T.A.; Corkum, D.L.; Friedman, L.J.; Hobbs, S.; Holz, M.; Liberman, S.; Nguyen, H.Q.; Resler, D.P.; Sharp, R.C.; Watson, E.A. Optical phased array technology. *Proc. IEEE* **1996**, *84*, 268–298. DOI: 10.1109/5.5482231.

McManamon, P.F.; Shi, J.; Bos, P.J. Broadband optical phased-array beamsteering. *Opt. Eng.* **2005**, *44*, 128004. DOI: 10.1117/1.2149374.

Resler, D.P.; Hobbs, D.S.; Sharp, R.C.; Friedman, L.J.; Dorschner, T.A. High-efficiency liquid-crystal optical phased-array beam steering. *Opt. Lett.* **1996**, *21*, 689–691. DOI: 10.1364/OL.21.000689.

Kiang, M.; Solgaard, O.; Lau, K.Y.; Muller, R.S. Electrostatic comb drive-actuated micromirrors for laser-beam scanning and positioning. *J. Microelectromech. Syst.* **1998**, *7*, 27–37. DOI: 10.1109/84.661381.

Stewart, J.B.; Bifano, T.G.; Cornelissen, S.; Bierden, P.; Levine, B.M.; Cook, T. Design and development of a 331-segment tip-tilt-piston mirror array for space-based adaptive optics. *Sens. Actuat. A Phys.* **2007**, *138*, 230–238. DOI: 10.1016/j.sna.2007.04.051.

Xie, H.; Pan, Y.; Fedder, G.K. A CMOS-MEMS mirror with curved-hinge comb drives. *J. Microelectromech. Syst.* **2003**, *12*, 450–457. DOI: 10.1109/JMEMS.2003.815839.

Jung, I.W.; Krishnamoorthi, U.; Solgaard, O. High fill-factor two-axis gimbaled tip-tilt-piston micromirror array actuated by self-aligned vertical electrostatic combdrives. *J. Microelectromech. Syst.* **2006**, *15*, 563–571. DOI: 10.1109/JMEMS.2006.876666.
[45] Tsai, J.C.; Wu, M.C. Design, fabrication, and characterization of a high fill-factor, large scan-angle, two-axis scanner array driven by a leverage mechanism. *J. Microelectromech. Syst.* 2006, 15, 1209–1213. DOI: 10.1109/JMEMS.2006.880291.

[46] Ryf, R.; Stuart, H.R.; Giles, C.R. MEMS tip/tilt & piston mirror arrays as diffractive optical elements. *Proc. SPIE Int. Soc. Opt. Eng.* 2005, 5894, 58940C. DOI: 10.1117/12.620566.

[47] Todd, S.T.; Jain, A.; Qu, H.; Xie, H. A multi-degree-of-freedom micromirror utilizing inverted-series-connected bimorph actuators. *J. Opt. A.* 2006, 8, 352–359. DOI: 10.1088/1464-4258/8/7/310.

[48] Wu, L.; Maley, S.; Nelson, T.; McManamon, P.; Xie, H. A large-aperture, piston-tip-tilt micromirror for optical phase array applications. In *Proceedings of the IEEE MEMS ’08*, Tucson, AZ, 2008; pp. 754–757. DOI: 10.1109/MEMSYS.2008.4443766.

[49] Yoo, B.W.; Megens, M.; Chan, T.; Sun, T.; Yang, W.; Chang-Hasnain, C.J.; Horsley, D.A.; Wu, M.C. Optical phased array using high contrast gratings for two dimensional beamforming and beamsteering. *Opt. Express* 2013, 21, 12238–12248. DOI: 10.1364/OE.21.012238.

[50] Pardo, F.; Cirelli, R.A.; Ferry, E.J.; Lai, W.Y.-C.; Klemens, F.P.; Miner, J.F.; Pai, C.S.; Bower, J.E.; Mansfield, W.M.; Kornblit, A.; et al. Flexible fabrication of large pixel count piston-tip-tilt mirror arrays for fast spatial light modulators. *Microelectron. Eng.* 2007, 84, 1157–1161. DOI: 10.1016/j.mee.2007.01.099.

[51] Srinivasan, U.; Helmbrecht, M.A.; Rembe, C.; Muller, R.S.; Howe, R.T. Fluidic self-assembly of micromirrors onto microactuators using capillary forces. *IEEE J. Select. Topics Quantum Electron.* 2002, 8, 4–11. DOI: 10.1109/2944.991393.

[52] Waldis, S.; Clerc, P.A.; Zamkotsian, F.; Zickar, M.; Noell, W.; Rooij, N.D. Micromirror arrays for object selection. In *Proceedings of the SPIE*, San Jose, CA, 6114; 2006; pp. 611408.1–611408.12. DOI: 10.1117/12.754184.

[53] Huang, M.C.Y.; Zhou, Y.; Chang-Hasnain, C.J. A surface-emitting laser incorporating a high-index-contrast subwavelength grating. *Nature Photon.* 2007, 1, 119–123. DOI: 10.1038/nphoton.2007.73.

[54] Karagodsky, V.; Chang-Hasnain, C.J. Physics of near-wavelength high contrast gratings. *Opt. Express* 2012, 20, 10888–10895. DOI: 10.1364/OE.20.010888.

[55] Yoo, B.W.; Megens, M.; Chan, T.; Sun, T.; Yang, W.; Chang-Hasnain, C.J.; Horsley, D.A.; Wu, M.C. A 32 × 32 optical phased array using polysilicon sub-wavelength high-contrast-grating mirrors. *Opt. Express* 2012, 22, 19029–19039. DOI: 10.1364/OE.22.019029.

[56] Yang, W.; Sun, T.; Rao, Y.; Megens, M.; Chan, T.; Yoo, B.W.; Horsley, D.A.; Wu, M.C.; Chang-Hasnain, C.J. High speed optical phased array using high contrast grating all-pass filters. *Opt. Express* 2014, 22, 20038–20044. DOI: 10.1364/OE.22.020038.

[57] Hu, W.; Peng, C.; Chang-Hasnain, C.J. Progress and prospects of silicon-based design for optical phased array. In *Proceedings of the SPIE*, High Contrast Metasurfaces, 9757, 2016; p. 97570U. DOI: 10.1117/12.2214155.

[58] Zhou, G.; Chau, F.S. Nondispersive optical phase shifter array using microelectromechanical systems based gratings. *Opt. Express* 2007, 15, 10958–10963. DOI: 10.1364/OE.15.010958.

[59] Wang, Y.; Zhou, G.; Zhang, X.; Kwon, K.; Blanche, P.-A.; Triesault, N.; Yu, K-S.; Wu, M.C. 2D Broadband beamsteering with large-scale MEMS optical phased array. *Optica* 2019, 6, 557–562. DOI: 10.1364/OPTICA.6.000557.

[60] Brazas, J.C.; Kowarz, M.W. 2004 High-resolution laser-projection display system using a grating electromechanical system (GEMS). In *Proceedings of SPIE*, MOEMS Display and Imaging Systems II, San Jose, California. DOI: 10.1117/12.531101.

[61] Zhou, G.; Lim, Z.H.; Qi, Y.; Zhou, G. Single-pixel MEMS imaging systems. *Micromachines* 2020, 11, 219. DOI: 10.3390/mi11020219.

[62] Zhou, G.; Du, Y.; Cheo, K.K.L.; Yu, H.; Chau, F.S. Optical scanning with MEMS in-plane vibratory gratings and its applications. In 2010 *International Conference on Optical MEMS and Nanophotonics*, Sapporo, 2010, 21–22. DOI: 10.1109/OMEMS.2010.5672205.

[63] Qiu, Z.; Liu, Z.; Duan, X.; Khondee, S.; Joshi, B.; Mandella, M.J.; Oldham, K.; Kurabayashi, K.; Wang, T.D. Vertical cross-sectional imaging with handheld near-infrared dual axes confocal fluorescence endomicroscope. *Biomed. Opt. Expr.* 2013, 4, 322–330. DOI: 10.1364/BOE.4.000322.

[64] Glennie, C.L.; Carter, W.E.; Shrestha, R.L.; Dietrich, W.E. Geometric imaging with airborne LiDAR: The Earth’s surface revealed. *Rep. Prog. Phys.* 2013, 76, 086801. DOI: 10.1088/0034-4885/76/8/086801.

[65] Zhang, K.; Yan, J.; Chen, S.C. Automatic construction of building footprints from airborne LIDAR data. *IEEE Trans. Geosci. Remote Sens.* 2006, 44, 2523–2533. DOI: 10.1109/TGRS.2006.874137.

[66] Hah, D.; Huang, S.Y.; Tsai, J.C.; Toshiyoshi, H.; Wu, M.C. Low-voltage, large-scan angle MEMS analog micromirror arrays with hidden vertical comb-drive actuators. *J. Microelectromech. Syst.* 2004, 13, 279–289. DOI: 10.1109/JMEMS.2004.825314.
Cheo, K.K.L.; Du, Y.; Zhou, G.; Chau, F.S. Post-corrections of image distortions in a scanning grating-based spectral line imager based on a MEMS vibratory grating scanner. In Proceedings of the SPIE 5249, Optical Design and Engineering, St. Etienne, France, 2004; p. 297. DOI: 10.1117/12.516540.

Zimmer, F.; Heberer, A.; Sandner, T.; Grueger, H.; Schenk, H.; Lakner, H.; Kenda, A.; Scherf, W. A new generation of MEMS middle-infrared spectrometers. In Proceedings of the SPIE 6466, MOEMS and Miniaturized Systems XIII, San Francisco, California, 2014; p. 89770F. DOI: 10.1117/12.2042679.

Yamamoto, Y.; Shinozaki, R.; Oka, Y.; Asahi, I.; Ninomiya, H.; Shimokawa, F.; Oohira, F.; Tako, H. A rotational MEMS diffraction grating for realization of micro-sized spectroscopy system. In Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS). Anchorage, AK, UAS, 2015; p. 15362512. DOI: 10.1109/TRANSUCERS.2015.7180898.

Pügnér, T.; Knobbe, J.; Grüger, H.; Schenk, H. Realization of a hybrid-integrated MEMS scanning grating spectrometer. In SPIE. Defense. Security and Sensing. Baltimore, MA, 2012; 8374. DOI: 10.1117/12.2004215.[10.1117/12.919068]

Zimmer, F.; Heberer, A.; Sandner, T.; Grueger, H.; Schenk, H.; Lakner, H.; Kenda, A.; Scherf, W. Investigation and characterization of high-efficient nir-scanning gratings used in nir micro-spectrometer. In Proceedings of the SPIE 6466, MOEMS and Miniaturized Systems VI, 2007; 646605. DOI: 10.1117/12.701821.

Kenda, A.; Kraft, M.; Wagner, C.; Lendl, B.; Wolter, A. MEMS-based spectrometric sensor for the measurement of Dissolved CO2. In Sensors, 2008 IEEE, Lecce, 2008; pp. 724–727. DOI: 10.1109/ICSENS.2008.4716544.

Pügnér, T.; Knobbe, J.; Grüger, H. Near-infrared grating spectrometer for mobile phone applications. Appl. Spectrosc. 2016, 70, 734–745. DOI: 10.1002/ASPC.2016638277.

Wen, Q.; Lei, H.; Huang, J.; Yu, F.; Huang, L.; Zhang, J.; Li, D.; Peng, Y.; Wen, Z. FR4-based electromagnetic grating scanning micro-grating with an angle sensor for a low-cost NIR micro-spectrometer. Appl. Opt. 2019, 58, 4642–4646. DOI: 10.1364/AO.58.004642.

Egloff, T.; Grüger, H.; Zimmer, F.; Schenk, H.; Scholles, M.; Lakner, H. NIR hyperspectral imaging using MOEMS scanning gratings chips and linear detector array. In Proceedings of the SPIE 6765, Next-Generation Spectroscopic Technologies, 2007; p. 67650F. DOI: 10.1117/12.734016.

Zhou, G.; Cheo, K.K.L.; Du, Y.; Chau, F.S.; Feng, H.; Zhang, Q. Hyperspectral imaging using a microelectrical-mechanical-systems-based in-plane vibratory grating scanner with a single photodetector. Opt. Lett. 2009, 34, 764–766. DOI: 10.1364/OL.34.000764.

Cheo, K.K.L.; Du, Y.; Zhou, G.; Chau, F.S. Post-corrections of image distortions in a scanning grating-based spectral line imager. IEEE Photon. Technol. Lett. 2013, 25, 1103–1106. DOI: 10.1109/LPT.2013.2258665.

Du, Y.; Cheo, K.K.L.; Zhou, G.; Chau, F.S. A spectral line imager based on a MEMS vibratory grating scanner. In 2012 International Conference on Optical MEMS and Nanophotonics, Banff, AB, 2012; pp. 210–211. DOI: 10.1109/ONMEMS.2012.6318877.

Keeler, B.E.N.; Carr, D.W.; Sullivan, J.P.; Friedmann, T.A.; Wendt, J.R. Experimental demonstration of a laterally deformable optical nanoelectromechanical system grating transducer. Opt. Lett. 2004, 29, 1182–1184. DOI: 10.1364/OL.29.001182.

Zhao, S.; Zhang, J.; Hou, C.; Bai, J.; Yang, G. Optical accelerometer based on grating interferometer with phase modulation technique. Appl. Opt. 2012, 51, 7005–7010. DOI: 10.1364/AO.51.007005.
Krishnamoorthy, U.; Olsson, R.H.; Bogart, G.R.; Baker, M.S.; Carr, D.W.; Swiler, T.P.; Clews, P.J. In-plane MEMS-based nano-g Accelerometer with sub-wavelength optical resonant sensor. Sens. Actuators A Phys 2008, 145–146, 283–290. DOI: 10.1016/j.sna.2008.03.017.

Hortschitz, W.; Steiner, H.; Sachse, M.; Stifter, M.; Kohl, F.; Schalko, J.; Jachimowicz, A.; Keplinger, F.; Sauter, T. Robust precision position detection with an optical MEMS hybrid device. IEEE Trans. Ind. Electron. 2012, 59, 4855–4862. DOI: 10.1109/TIE.2011.2173096.

Olsson, R.H.; Keeler, B.E.N.; Czaplewski, D.A.; Carr, D.W. Circuit Techniques for Reducing low frequency noise in optical MEMS position and inertial sensors. In IEEE International Symposium on Circuits and Systems, 2007; 2391–2394. DOI: 10.1109/ISCAS.2007.377941.

Zhang, M.; Wu, G.; Ren, D.; Gao, R.; Qi, Z.M.; Liang, X. An optical MEMS acoustic sensor based on grating interferometer. Sensors 2019, 19, 1503. DOI: 10.3390/s19071503.

Williams, R.P.; Hord, S.K.; Hall, N.A. Optically read displacement detection using phase-modulated diffraction gratings with reduced zeroth-order reflections. Appl. Phys. Lett. 2017, 110, 151104. DOI: 10.1063/1.4979541.

Hortschitz, W.; Steiner, H.; Sachse, M.; Stifter, M.; Kohl, F.; Schalko, J.; Jachimowicz, A.; Keplinger, F.; Sauter, T. An optical in-plane MEMS vibration sensor. IEEE Sens. J. 2011, 11, 2805–2812. DOI: 0.1109/JSEN.2011.2169781. DOI: 10.1109/JSEN.2011.2169781.

Sola, O.; Sandejas, F.S.A.; Bloom, D.M. Deformable grating optical modulator. Opt. Lett. 1992, 17, 688–690. DOI: 10.1364/OL.17.000688.

Apte, R.B.; Sandejas, F.; Banyai, W.; Bloom, D.M. Deformable grating light valves for high resolution displays. In Solid State Sensors and Actuators Workshop Hilton Head Island, SC, Jun. 13–16, 1994. DOI: 10.1109/IEDM.1994.383397.

Zamkotsian, F.; Timotijevic, B.; Lockhart, R.; Stanley, R.P.; Lanzoni, P.; Luetzelschwab, M.; Canonica, M.; Noell, W.; Tormen, M. Optical characterization of fully programmable MEMS diffraction gratings. Opt. Express. 2012, 20, 25267–25274. DOI: 10.1364/OE.20.025267.

Bloom, D.M. 1997 The grating light valve: revolutionizing display technology. Proc. SPIE 3013, 165–171. DOI: 10.1117/12.273686.

Amm, D.T.; Corrigan, R.W. Optical performance of the grating light valve technology. In Proceedings of the SPIE 3634, Projection Displays V, San Jose, California, 1999. DOI: 10.1117/12.349346.

Payne, A.; DeGroot, W.; Monteverde, R.; Amm, D. Enabling high-data-rate imaging applications with grating light valve technology. In Proceedings of the SPIE 5348, MOEMS Display and Imaging Systems II, San Jose, California, 2004. DOI: 10.1117/12.525886.

Verheggen, J.; Panaman, G.; Castracane, J. Characterization and fabrication of MOEMS-based diffractive optical switching elements. In Proceedings of the SPIE 6114, MOEMS Display, Imaging, and Miniaturized Microsystems IV, 2006; p. 61140. DOI: 10.1117/12.647806.

Suresh, V.G.; DasGupta, N.; Bhattacharya, S. Tunable MEMS diffraction gratings. Proc. SPIE 2012, 8549, 854918. DOI: 10.1117/12.925113.

Rudra, S.; Roels, J.; Bryce, G.; Haspeslagh, L.; Witvrouw, A.; Van Thourhout, D. SiGe based grating light valves: A leap towards monolithic integration of MOEMS. Microelectron. Eng 2010, 87, 1195–1197. DOI: 10.1016/j.mee.2009.12.015.

Kostsov, E.G. Ferroelectric-based electrostatic micromotors with nanometer Gaps. IEEE Trans. Ultrason. Ferroelectr Freq. Control 2006, 53, 2294–2298. DOI: 10.1109/TUFFC.2006.176.

Kostsov, E.G.; Sobolev, V.S. Low-voltage element of a field-programmable dynamic diffraction grating. Optoelectroninstrumentproc. 2010, 46, 287–293. DOI: 10.3103/S875669901003012X.

Yun, S.K.; et al. A novel diffractive micro-optical modulator for mobile display applications. In Proc. SPIE 6887, MOEMS and Miniaturized Systems VII, San Jose, California, 2008; 688702. DOI: 10.1117/12.762568.

Loh, N.C.; Schmidt, M.A.; Manalis, S.R. Sub-10cm3 interferometric accelerometer with nano-g resolution. J. Microelectromech. Syst. 2002, 11, 182–187. DOI: 10.1109/JMEMS.2002.1007396.

Lee, F.; Zhou, G.; Yu, H.; Chau, F.S. A MEMS-based resonant-scanning lamellar grating Fourier transform micro-spectrometer with laser reference system. Sens. Actuat. A Phys. 2009, 149, 221–228. DOI: 10.1016/j.sna.2008.12.002.

Hocker, G.B.; Youngner, D.; Deutsch, E.; Volpicelli, A.; Senturia, S.; Butler, M.; Sinclair, M.; Plowman, T.; Ricco, A.J. The polychromator: A programmable MEMS diffraction grating for synthetic spectra. In Proceedings of the Tech. Digest of Solid-State Sensors and Actuators Workshop, Transducers Research Foundation, Cleveland Heights, OH, 2000; pp. 89–92.

Li, X.; Antoine, C.; Lee, D.; Wang, J.S.; Solgaard, O. Tunable blazed gratings. J. Microelectromech. Syst. 2006, 15, 597–604. DOI: 10.1109/JMEMS.2006.872241.

Burns, D.M.; Bright, V.M. Micro-electro-mechanical variable blaze gratings. In IEEE MEMS, Nagoya, Japan, 1997; pp. 55–60. DOI: 10.1109/MEMSYS.1997.581765.
[111] Krishnamoorthy, U.; Li, K.; Yu, K.; Lee, D.; Heritage, J.P.; Solgaard, O. Dual-mode micromirrors for optical phased array applications. Sens. Actuators A Phys. 2002, 97–98, 21–26. DOI: 10.1016/S0924-4247(01)00814-7.

[112] Yu, Y.T.; Yuan, W.Z.; Qiao, D.Y. Electromechanical characterization of a new micro programmable blazed grating by laser Doppler vibrometry. Microsyst. Technol. 2009, 15, 853–858. DOI: 10.1007/s00542-009-0835-0.

[113] Yu, Y.T.; Yuan, W.Z.; Qiao, D.Y.; Yan, B. A simple numerical method to study the far-field diffraction of optical MEMS devices with a large array and complex element geometry. Sens. Actuators A Phys. 2010, 158, 30–36. DOI: 10.1016/j.sna.2009.12.032.

[114] Minne, S.C.; Manalis, S.R.; Quate, C.F. Parallel atomic force microscopy using cantilevers with integrated piezoresistive sensors and integrated piezoelectric actuators. Appl. Phys. Lett. 1995, 67, 3918–3920. DOI: 10.1063/1.115317.

[115] Manalis, S.R.; Minne, S.C.; Atalar, A.; Quate, C.F. Interdigital cantilevers for atomic force microscopy. Appl. Phys. Lett. 1996, 69, 3944–3946. DOI: 10.1063/1.117578.

[116] Yaralioglu, G.G.; Atalar, A.; Manalis, S.R.; Quate, C.F. Analysis and design of an interdigital cantilever as a displacement sensor. J. Appl. Phys. 1998, 83, 7405–7414. DOI: 10.1063/1.367984.

[117] Cooper, E.B.; Post, E.R.; Griffith, S.; Levitan, J.; Manalis, S.R.; Schmidt, M.A.; Quate, C.F. High-resolution micromachined interferometric accelerometer. Appl. Phys. Lett. 2000, 76, 3316–3318. DOI: 10.1063/1.126637.

[118] Selvakumar, A.; Ayazi, A.F.; Najafi, K. A high sensitivity z-axis torsional silicon accelerometer. In Proceedings of the SPIE, MOEMS Display, Imaging, and Miniaturized Microsystems IV; 2006; pp. 6114, 611 40C-1

[119] Aydin, O.; Akin, T. A bulk-micromachined fully differential MEMS accelerometer with split interdigitated fingers. IEEE Sensors J. 2013, 13, 2914–2921. DOI: 10.1109/JSEN.2013.2264667.

[120] Wong, C.W.; Jeon, Y.; Barbastathis, G.; Kim, S.G. Analog tunable gratings driven by thin-film piezoelectric microelectromechanical actuators. Appl. Opt. 2003, 42, 621–626. DOI: 10.1364/AO.42.000621.

[121] Shih, W.C.; Kim, S.G.; Barbastathis, G. High-resolution electrostatic analog tunable grating with a single-mask fabrication process. J. Microelectromech. Syst. 2006, 15, 763–769. DOI: 10.1109/JMEMS.2006.879369.

[122] Wong, C.W.; Jeon, Y.; Barbastathis, G.; Kim, S.G. Analog piezoelectricdriven tunable gratings with nanometer resolution. J. Microelectromech. Syst. 2004, 13, 998–1005. DOI: 10.1109/JMEMS2004.839592.

[123] Tormen, M.; Peter, Y.A.; Niedermann, P.; Hoogerwerf, A.; Shea, H.; Stanley, R. Deformable MEMS grating for wide tunability and high operating speed. In Proceedings of the SPIE, MOEMS Display, Imaging, and Miniaturized Microsystems IV; 2006; pp. 6114, 611 40C-1–611 40C-11. DOI: 10.1117/12.644523.

[124] Yu, Y.T.; Yuan, W.Z.; Li, T.P.; Yan, B. Development of a micromechanical pitch-tunable grating with reflective/transmissive dual working modes. J. Micromech. Microeng. 2010, 20, 065002. DOI: 10.1088/0960-1317/20/6/065002.

[125] Zhou, G.; Dowd, P. Tilted folded-beam suspension for extending the stable travel range of comb-drive microcantilevers. J. Micromech. Microeng. 2003, 13, 178–183. DOI: 10.1088/0960-1317/13/2/303.

[126] Yu, Y.T.; Yuan, W.Z.; Sun, R.; Qiao, D.; Yan, B. A strategy to efficiently extend the change rate of period for comb-drive micromechanical pitch-tunable gratings. J. Microelectromech. Syst. 2010, 19, 1180–1185. DOI: 10.1109/JMEMS.2010.2067205.

[127] Yang, Y.S.; Lin, Y.H.; Hu, Y.C.; Liu, C.H. A large-displacement thermal actuator designed for MEMS pitch-tunable grating. J. Micromech. Microeng. 2008, 19, 015001. DOI: 10.1088/0960-1317/19/1/015001.

[128] Muttukulangara, S.S.; Baranski, M.; Rehman, S.; Hu, L.; Miao, J. Mems tunable diffraction grating for spaceborne imaging spectroscopic applications. Sensors 2017, 17, 2372. DOI: 10.3390/s17102372.

[129] Yan, D.; Lal, A. Design and characterization of slit variable microgratings. IEEE Sens. J. 2006, 6, 458–464. DOI: 10.1109/JSEN.2006.870150.

[130] Hane, K.; Kobayashi, T.; Hu, F.R.; Kanamori, Y. Variable optical reflectance of a self-supported Si grating. Appl. Phys. Lett. 2006, 88, 141109. DOI: 10.1063/1.2193989.

[131] Zhang, W.M.; Yan, H.; Peng, Z.K.; Meng, G. Electrostatic pull-in instability in MEMS/NEMS: A review. Sens. Actuat. A Phys. 2014, 214, 187–218. DOI: 10.1016/j.sna.2014.04.025.

[132] Liu, X.; Li, T.; Ming, A.; Wang, Y. A compressed wide period-tunable grating working at low voltage. J. Semicond. 2010, 31, 104010. DOI: 10.1088/0964-6969/31/10/104010.

[133] Zhang, X.M.; Liu, A.Q. A MEMS pitch-tunable grating add/drop multiplexers. Proc. IEEE/LEOS Int. Conf. Opt. MEMS, Kauai, Hawaiian, 2000, 25–26. DOI: 10.1109/OMEMS.2000.879610.

[134] Deterre, M.; Nichol, A.J.; Oh, S.B.; Barbastathis, G. Analog and digital deformable diffractive optics actuated by inter-nanomagnet forces. IEEE J. Quantum Electron. 2010, 46, 1275–1287. DOI: 10.1109/JQE.2010.2046721.
Wang, Y.; Kanamori, Y.; Sasaki, T.; Hane, K. Design and fabrication of freestanding pitch-variable blazed gratings on a silicon-on-insulator wafer. J. Micromech. Microeng. 2009, 19, 025019. DOI: 10.1088/0960-1317/19/2/025019.

Wang, Y.; Kanamori, Y.; Sasaki, T.; Hane, K. Pitch-variable blazed grating consisting of freestanding silicon beams. Opt. Express 2009, 17, 4419–4426. DOI: 10.1364/OE.17.004419.

Yang, Y.S.; Liu, C.H. Design and fabrication of pitch-tunable blaze gratings. In Proceedings of the SPIE 5717, MEMS/MOEMS Components and Their Applications II, 2005. DOI: 10.1117/12.590020.

O’Halloran, A.; O’Malley, F.; McHugh, P. A review on dielectric elastomer actuators, technology, applications, and challenges. J. Appl. Phys. 2008, 104, 071101. DOI: 10.1063/1.2981642.

Ashchwanden, M.; Beck, M.; Stemmer, A. Diffractive transmission grating tuned by dielectric elastomer actuator. IEEE Photon. Technol. Lett. 2007, 19, 1090–1092. DOI: 10.1109/LPT.2007.900555.

Li, Y.; Jia, S.; Wang, H.; Chen, D.; Hane, K. Pitch-variable transmission-type bulk gratings driven by shape memory alloy actuator. Opt. Laser Technol. 2002, 34, 649–653. DOI: 10.1016/S0030-3992(02)00089-0.

Wang, F.; Jia, S.; Wang, Y.; Tang, Z. Near-infrared light-controlled tunable grating based on graphene/elastomer composites. Opt. Mater. 2018, 76, 117–124. DOI: 10.1016/j.optmat.2017.12.004.

Patel, S.K.; Ladumor, M.; Sorathiya, V.; Guo, T. Graphene based tunable grating structure. Mater. Res. Expr. 2018, 6, 025602. DOI: 10.1088/2053-1591/aaea9a.

Wu, M.C.; Solgaard, O.; Ford, J.E. Optical MEMS for lightwave communication. J. Lightwave Technol. 2006, 24, 4433–4454. DOI: 10.1109/JLT.2006.886405.

Verheggen, J.P.; Khan-Raja, W.; Castracane, J. Optimization of diffractive MEMS for optical switching. J. Exp. Nanosci. 2007, 2, 87–100. DOI: 10.1080/17458080601024188.

Yu, Y.T.; Yuan, W.Z.; Yan, B.; Li, T.P. Development of a micromechanical grating optical modulator for optical network. J. Micro. Nanolithogr. MEMS MOEMS 2005, 4, 041401. DOI: 10.1117/1.2107687.

Mariette, A.; Elphic, R.C.; Heldmann, J.; Ennico, K. An overview of the lunar crater observation and sensing satellite (LCROSS). Space Sci. Rev. 2012, 167, 3–22. DOI: 10.1007/s11214-012-9880-6.