Gaussian beam coupling on a MEMS mirror array

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A B S T R A C T
A general formula for evaluating Gaussian beam coupling characteristics on a MEMS mirror array was developed, with consideration of parameters such as beam size, mirror width and mirror gap. Based on the formula, the influence of each parameter on the spectral response was simulated for MEMS mirror array employed in a wavelength selective switch and a tunable optical filter. The simulation results are helpful for the design of MEMS mirror array in optical devices.

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1. Introduction

The dynamic optical sub-systems, such as reconfigurable optical add/drop multiplexer (ROADM), optical cross connect (OXC) and optical performance monitor (OPM), are key components for dynamic optical network [1]. The new generation of ROADM and OXC consisting of wavelength selective switches (WSS) show most flexibility in wavelength management [2,3], while the tunable optical filter (TOF) is an important via for OPM modules [4]. The MEMS mirror array, serving as the spatial light modulator (SLM), is a popular approach to construct a dynamic optical device, such as a WSS or a TOF [5–9].

In the MEMS-based dynamic optical devices, the broadband optical signal or DWDM (dense wavelength division multiplexing) signal is first dispersed by a grating and then focused on the mirror array by a Fourier lens. The optical beam of different wavelength spreads on the mirror array linearly and the reflection spectrum is adjustable by independent control of the individual mirrors. The spectral response of a 1 × N WSS and a 1 × N^2 WSS was analyzed in [6] and [10] respectively. The former focused on the influence of the confinement ratio (the ratio between the mirror width and the beam size), while the latter addressed the interchannel response of the horizontal output ports. In [11], the characteristics of a fiber switch based on a pixelized phase modulator was analyzed, where the output ports were horizontally aligned with the input port and each signal channel was steered by several pixelized mirrors.

This paper addresses Gaussian beam coupling on a MEMS mirror array, with consideration of parameters such as the beam size, mirror width and mirror gap. The beam steering direction is vertical to the mirror array. The Gaussian beam may be confined in a single mirror or cover multiple adjacent mirrors, corresponding to applications in a WSS or a TOF respectively.

2. Theoretical model

The MEMS mirror array serves as the SLM in a dynamic optical device. For application in a WSS, the focused DWDM beams are confined in a single mirror each, as shown in Fig. 1(a). While for application in a TOF, the focused broadband optical beam cover multiple adjacent mirrors, as shown in Fig. 1(b). The mirror width, mirror pitch and the focused beam width in the dispersion direction is expressed as D, P and 2ωx respectively. The optical beam of different wavelength spreads on the mirror array incrementally from short wavelength λs to long wavelength λl. The spectral response of the optical device is determined by the coupling characteristics of the Gaussian field on the mirror array.

The Gaussian field dispersed and focused on the MEMS mirror array is given by [6]

\[
\psi(x, y) = \left( \frac{2}{\pi \omega^2} \right)^{1/4} \exp \left[ -\left( \frac{x - D_f y}{\omega x} \right)^2 \right] 
\]

(1)

where \( D_f \) is the linear dispersion of the grating-lens combination before the mirror array.

\[
D_f = \frac{fc}{\nu^2 d \cos \theta}
\]

(2)
where $c$ is the light velocity, $f$ is the focal length of the Fourier lens, $d$ is the grating period and $\theta$ is the diffraction angle.

The product $D \nu$ determines the center position of the Gaussian field for frequency $\nu$. Here we suppose that the mirror height is enough to confine the Gaussian beam and thus the item with $y$ coordinate is neglected.

The frequency-dependent power-coupling efficiency on the mirror array is given by the overlap integral

$$\eta(\nu) = \left[ \int \psi(x, \nu) \psi^*(x, \nu) \, dx \right]^2$$

(3)

The integrating range is over the extent of the mirrors in alignment except for the gap between mirrors, i.e.

$$x \in (nP - 0.5D, nP + 0.5D), \quad n = -\frac{N}{2}, -\frac{N}{2} + 1, \ldots, \frac{N}{2}$$

(4)

where $N$ is the total number of mirrors in alignment.

According to Eqs. (1)–(4), the power-coupling efficiency and spectral transmittance are obtained as

$$\eta(\nu) = \frac{1}{4} \sum_{n=-N/2}^{N/2} \left\{ \text{erf} \left[ \sqrt{\frac{2}{\alpha_0}} (np + 0.5D - Di) \right] - \text{erf} \left[ \sqrt{\frac{2}{\alpha_0}} (np - 0.5D - Di) \right] \right\}^2$$

(5)

$$T(\nu) = -10 \log[\eta(\nu)]$$

(6)

3. Simulation results

According to Eqs. (5) and (6), the spectral response of the Gaussian beam coupling on a MEMS mirror array depends on the parameters $D, P$ and $\omega_0$. For different applications, such as in a WSS or in a TOF, the ratio between the mirror size and the beam size is reverse, and thus the devices show different spectral response.

3.1. Application in a WSS

For application in a WSS, the mirror size is more than the beam size and thus the DWDM beams are confined in a single mirror each. The DWDM signals are directed to their destination ports by proper steering of the individual mirrors.

![Fig. 1](image1.png)

**Fig. 1.** Gaussian beam and MEMS mirror array, (a) for a WSS, (b) for a TOF, $P$-mirror pitch, $D$-mirror width, $2\omega_0$-Gaussian beam width, $\lambda_s$-short wavelength, $\lambda_l$-long wavelength.

![Fig. 2](image2.png)

**Fig. 2.** The influence of mirror gap on the spectral response of a WSS, all the mirrors are aligned to the same output port, (a) the mirror gap $\Delta$ and the confinement factor $\xi$ are fixed, (b) the gap to beam ratio $\delta$ is fixed.

The linear dispersion is designed as $D_l = P/\nu_{ch}$, where $\nu_{ch}$ is the channel spacing between the DWDM signals. Thus Eq. (5) is simplified as

$$\eta(\nu) = \frac{1}{4} \left\{ \text{erf} \left[ \sqrt{\frac{2}{\alpha_0}} (2n + \frac{\Delta}{2\omega_0} - 1) \right] - \text{erf} \left[ \sqrt{\frac{2}{\alpha_0}} (2n + \frac{\Delta}{2\omega_0} - 1) \right] \right\}^2$$

(7)

where $\tau = D/P$ is the fill ratio of the mirror array and $\xi = D/2\omega_0$ is the confinement factor between the mirror and the Gaussian beam.

The spectral response under different confinement factor was demonstrated in [6]. A larger confinement factor improves the passband, while the gap $\Delta = P - D$ between mirrors results in spectrum pits between DWDM channels. The mirror gap should be designed as small as possible, while the minimal value is limited by the fabrication process.

**Fig. 2(a)** shows the spectral response under a given confinement factor $\xi = 2$ and a fixed mirror gap $\Delta$. With the increment of the fill ratio $\tau$, the beam size $2\omega_0$ increases and the mirror gap to beam size ratio $\delta = \Delta/2\omega_0$ decreases, which results in reduction of pits between DWDM channels. Meanwhile, the passband shows minor difference. **Fig. 2(b)** shows the spectral response under a fixed ratio $\delta$. With the increment of the fill ratio $\tau$, the confinement factor $\xi$ improves and the passband increases, while the spectrum pits remain constant.

The above results show that the depth of the pits depends on the mirror gap to beam size ratio $\delta$. The more is the ratio $\delta$, the deeper are the pits in the spectrum.
3.2. B. Application in a TOF

For application in a TOF, the mirror width is much small and the Gaussian beam covers multiple adjacent mirrors. The passband wavelength and width of the TOF are decided by the location and number of the mirrors aligned to the output port.

Under a given linear dispersion $D$, Eq. (5) is simplified as

$$\eta(v) = \frac{1}{4} \sum_{k=-N/2}^{N/2} \left\{ \text{erf} \left[ \sqrt{2} \xi_1 \left( \frac{2n}{\tau} + 1 - \frac{2Dv}{\tau^2} \right) \right] - \text{erf} \left[ \sqrt{2} \xi_1 \left( \frac{2n}{\tau} + 1 - \frac{2Dv}{\tau^2} \right) \right] \right\}^2$$

where $\xi_1 = D/2\omega_b$ is the confinement factor between a single mirror and the Gaussian beam, which is distinguished from the confinement factor $\xi_m = nD/2\omega_b$ between multiple mirrors and the Gaussian beam.

For convenience of simulation, we choose the parameters as follow. The grating line density is 1200 lines/mm. For wavelength $\lambda_c = 1550$ nm, the incident and diffraction angle on the grating is $\varphi = \theta = 68.4^\circ$. The focal length of the Fourier lens is $f = 100$ mm. Thus the linear dispersion is $D = 2.568$ $\mu$m/GHz according to Eq. (2).

The ratio $m = 2\omega_m/\xi$ between the beam size and the mirror pitch means the number of mirrors covered by a Gaussian beam. Simulation results in Fig. 4 indicate that the passband ripple decreases with the increment of $m$. However, the increment of $m$ means that we need more and narrower mirrors, which will add to difficulty in fabrication of the mirror array. In the following simulation, we suppose that $m = 2$, which is enough to reduce the ripple to <0.1 dB.

Simulation results in Fig. 5 show the influence of the fill ratio of the mirror array. The transmittance of the TOF increases when the fill ratio is improved. The insertion loss can be estimated as

$$IL = -10 \cdot \log(\tau^2)$$

That is, a fill ratio of $\tau = 90\%$ will result in a insertion loss of 0.92 dB.

The passband of the TOF is determined by the order and number of mirrors aligned to the output port. When the confinement factor by multiple mirrors is $\xi_m = 1$ (i.e. the number of mirrors in alignment is $N = 2$), we obtain the narrowest 3 dB line width $\Delta \lambda = 0.1$ nm (i.e. 12.5 GHz), as shown in Fig. 5. When the order of mirrors in alignment is shifted by one pitch, the wavelength tuning resolution is obtained as 0.04 nm.
When the MEMS mirror array consists 1000 mirrors in pitch of 13 \( \mu m \), the wavelength tuning range of the TOF extends from 1530 nm to 1570 nm, covering the C-band of optical fiber, as shown in Fig. 7.

The TOF based on MEMS mirror array also shows tunability on passband width. With the increment of the confinement factor \( \xi_m \), the passband width expands to cover multiple DWDM channels, as shown in Fig. 8.

4. Conclusion

For dynamic optical devices employing a MEMS mirror array, the spectral response depends on the Gaussian beam coupling characteristics on the mirror array. We have developed a general formula for the spectrum analysis and obtained a series of simulation results. For application in a WSS, we addressed the issues such as the spectrum pits between channels, the passband width and the crosstalk level. For application in a TOF, the passband ripple, the insertion loss, the wavelength tuning resolution and tuning range, the passband width tunability were analyzed. These results are helpful for the design of MEMS mirror array in optical devices.

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