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Spatial and spectral beam shaping with space-variant guided mode resonance filters

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Abstract: Novel all-dielectric beam shaping elements were developed based on guided mode resonance (GMR) filters. This was achieved by spatially varying the duty cycle of a hexagonal-cell GMR filter, to locally detune from the resonant condition, which resulted in modified wavelength dependent reflection and transmission profiles, across the device aperture. This paper presents the design, fabrication, and characterization of the device and compares simulations to experimental results.

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Introduction

Graded reflectivity mirrors have been widely used in laser cavities for mode control and output beam shaping [1]. These mirrors operate by preferentially increasing the loss for selected transverse laser cavity modes. Convex Gaussian reflectivity profile mirrors have been demonstrated to improve the far-field laser output beam profile [2,3]. The operation of a resonator with a Gaussian spatial reflectivity mirror increases the total power output of the laser [4]. The beam quality enhancement is particularly attractive for high power lasers. The larger waveguides, required to achieve higher laser gain, result in a multimode output beam. A graded reflectivity mirror in conjunction with an intra-cavity phase element has been used to demonstrate near fundamental mode operation of the laser cavity [5]. More recently, it has been shown that quasi-Gaussian output beams can be achieved, in a resonator configuration, by matching the highs and lows of the space variant mirror reflection to the field modulation. This method exploits the self imaging properties of a multimode waveguide of discrete length, placed between two mirrors, in conjunction with the spatial reflectance profiles to control modal discrimination [6]. Spectrally spatial beamshaping can also be performed with concatenated waveguides through multimode interference (MMI) effects, resulting in frequency dependent shaping of transmitted beams, by adjusting the waveguide length to coincide with the predicted location of the desired beam shape within the waveguide [7]. Space variant frequency dependent reflection surfaces have also been implemented using frustrated total internal reflection [8].

Techniques for realizing graded reflectivity mirrors are limited and depend on complicated deposition techniques [9,10]. These mirrors provide a phase shift to the reflected and transmitted beams, which may be undesirable in certain cases. Any non-uniformity in the films can lead to performance deviations from the designed response. Apodized grating-based mirrors have been explored to generate space variant reflection. They include variable depth gratings operated in Littrow configuration, and variable duty cycle amplitude gratings that scatter the higher diffracted orders outside the laser cavity [5,11]. However, these structures have larger losses due to the associated scattering and absorption.

In this paper, we propose and demonstrate all-dielectric guided-mode resonance (GMR) filters with space variant functionality, to provide frequency dependent spatial reflection and transmission. Figure 1 shows the conceptual operation of the proposed device. Guided mode resonance filters have been widely used as narrow band spectral filters [12,13]. In a typical
configuration, such filters are constructed by placing a sub-wavelength grating in contact with a waveguiding layer. At the resonance wavelength, the grating couples the external waves into guided modes within the slab. The grating also out-couples the guided radiation to produce sharp transmission and reflection responses around the resonance. A standard GMR filter was recently applied as a feedback element in a fiber laser resonator [14]. The resonant condition of the filter is a function of the grating lattice structure, optical thickness, period, duty cycle and the optical thickness of the guiding layer [15]. A graded reflection profile can be obtained from a free space GMR filter, by spatially varying the duty cycle of the unit-cell phase function across the incident beam aperture. The duty cycle variation induces localized changes in the frequency-dependent coupling conditions across the device, and this effect can be exploited to generate graded reflection spatial profiles from the filter with spectrally selective properties. The ability to obtain frequency-dependent reflection from these filters is attractive for laser applications [8].

Device concept

The structure of our GMR filter is schematically illustrated in Fig. 2(a). It consisted of a silicon oxide (SiO$_x$) layer patterned with a hexagonal grating structure and a silicon nitride (Si$_x$N$_y$) guiding layer deposited on a fused silica substrate. The spectral response of a GMR structure, of infinite spatial extent under plane wave illumination, was simulated using rigorous coupled-wave analysis (RCWA), as a function of the hexagonal unit-cell feature diameter ($d$) [16]. The results are shown in Fig. 2(b). As the diameter of the holes in the grating layer was increased, the spectral reflection peak was blue shifted, due to the decreased effective index of the coupling condition. For small variations in the hole diameter, the change of the resonance location is approximately linear, and the linewidth remains unchanged. Excellent side lobe suppression ratios were achieved as well as high peak reflection on resonance.

The simulated spectral reflection peak from the filter is shown in Fig. 3(a). The design was optimized to provide a wide spectral reflection peak. The spectral linewidth from a GMRF single resonance, with constant duty cycle across the hex-grating, was ~3nm for our design. As the linewidth of the designed spectral reflection was increased, the full width at half maximum (FWHM) of the reflection variation with duty cycle curve, shown in Fig. 3(b), was enlarged. The peak reflection as a function of feature size was dependent upon the illumination wavelength. As the wavelength of illumination was red-shifted, the peak reflection was obtained for a larger patterned feature diameter. The space variant GMR was
designed by setting the hex-grating duty cycle according to the simulation results, so as to locally define the out-coupled light intensity.

The transmission and reflection profiles for an incident Gaussian beam passing through the guided-mode filter element with space-variant duty cycles were calculated subsequently. In the case of a GMR with a large duty cycle variation range, the transmission and reflection profile showed sharp drops and peaks that have a wavelength-dependent spatial location within the beam. The duty cycle variation range across the device was designed to be smaller than the FWHM of the curves shown in Fig. 3(a). The transmission and reflection beam profiles, resulting from an incident plane wave with Gaussian beam profile, were also a function of the type of duty cycle variation across the device. The transmitted and reflected beam profiles shown in Fig. 4 (a) and (c), correspond to a feature size that increases linearly from the center of the GMR device as a function of the radial location outward. The linear variation in duty cycle provides different beam profiles below the nominal resonance (1549.3nm), at the nominal resonance (1550.7nm) and, above resonance (1552.8nm). The nominal resonant wavelength for the space variant GMR, corresponds to the spectral location of the peak obtained from an unmodulated GMR, with a duty cycle that is the same as those found at the center of the space variant GMR. Below resonance, a quasi-flat top transmission profile was obtained and the spatial reflection had a central peak. As the illuminating wavelength approached the spectral nominal resonance peak (1550.7nm), the transmission profile had a central null with an increased peak in reflection. This was because the beam incident on the center of the GMR encounters a large reflection. Above the nominal resonance, the inner rings of the space variant GMR transmit while the outer rings reflect resulting in an apodized beam in transmission and central null in reflection. As the illumination wavelength was moved further away from the spatial resonance, the spatial width of the apodized transmission increased.

The transmitted and reflected beam profiles, for a hole feature size width a quadratic dependence on the radial location, are shown in Fig. 4 (b) and (d). These profiles are significantly different from those obtained for a linear duty cycle variation. Below resonance, apodized beam profile was obtained in transmission and in reflection. At resonance, the transmitted beam has a quasi flat-top profile with a reduced aspect as compared to the linear duty cycle variation condition and an apodized beam in reflection. Above nominal resonance, an apodized beam was obtained in transmission and a quasi flat-top with reduced aspect in
reflection. The space variant GMR mirror thus provides frequency dependent beam profiles that depend directly on the functional form of the duty cycle variation.

![Simulated Beam Profiles](image)

Fig. 4. Simulated transmission profiles for an incident Gaussian beam when the radial increase in feature size from the center of the grating layer of the GMR device has: (a) a linear dependence and, (b) a quadratic dependence. Simulated reflection profiles when the radial increase in feature size from the center of the grating layer of the GMR device has: (c) a linear dependence and, (d) a quadratic dependence.

**Graded reflection mirror fabrication**

Several methods for varying the duty cycle, as a function of spatial location, have been demonstrated for different applications. Among them electron beam lithography is a popular technique since it can achieve smooth variations in duty cycle and fast local variations. A novel technique, that uses the linear regime of the photoresist response curve to add binary and analog intensity profiles, was used to achieve uniform smooth variations in grating duty cycle, and fast local variations with high patterning fidelity across the GMR optical element [17]. This technique will be described briefly for the sake of completeness. The concept used to create the space variant gratings is schematically illustrated in Fig. 5. The latent image of the desired binary grating unit-cell function was first created using an exposure that was very close to saturation dose ($U(x,y)$). Figure 5(a) shows the schematic of the unit-cell aerial image intensity, from an amplitude grating, which was obtained at the wafer plane of the GCA g-line stepper tool. Since the period of the designed grating (1.15µm) was below the resolution of the stepper tool, a multiple exposure technique was used to fabricate the grating structures, starting with a unit cell of twice the desired period (2.30µm) [18]. Analog intensity profiles ($A(Xn, Ym)$) generated from a phase-only mask, that modulates the spatial-intensity profile at the wafer plane, was subsequently overlaid on the initial grating exposure, prior to photoresist development. The latent image formation process can be described as:
In Eq. (1), \( L(d) \) is the final latent image, representing a function of the grating hole variation across the global grating coordinates \( X \) and \( Y \), as a global replication of the grating unit cell image \( U \) (with local coordinates \( x \) and \( y \)), to which is added the overlay amplitude variation \( A(X,Y) \), in \( n \) and \( m \) functional powers. A two-dimensional linear variation of the hole sizes across the diagonal of the grating plane, will require the powers to be \( n = m = 1 \), whereas a one-dimensional linear hole distribution will require either \( n = 0; m = 1 \) or \( n = 1; m = 0 \).

The phase-only masking technique described above to generate the continuously varying spatial intensity profiles was originally developed to create surface relief micro-optical elements and structures [19]. The intensity profile used in our overlay exposure was originally designed to create a lens profile, with a square base in photoresist, shown in Fig. 5(b) \((n = m = 2)\). The minimum feature size, or the largest duty cycle on the grating, was controlled by the initial exposure \((U(x,y))\) and the minimum intensity of the space-variant exposure profile \((\text{min}(A(X,Y)))\). The maximum and minimum duty cycle obtained across the GMR element, can be effectively controlled, by changing the overlay exposure dose value. The schematic of the space variant grating obtained using this novel technique post-development, is shown in Fig. 5(c). The local duty cycle of the patterned features is a function of the local dose received, as a sum of the uniform grating exposure and the space-varying exposure of the overlayed profile. Decoupling the grating latent image formation and the spatial line-width modulation facilitates arbitrary duty cycle variation designs to be reliably achieved. Other techniques, such as gray scale and half tone masking, which provide space variant exposure intensity at the wafer plane, may also be used in the overlay exposure.

Fig. 5. (a) Schematic of the aerial image intensity \((U(x,y))\) at the wafer plane of a lithographic stepper tool from a hexagonal grating unit-cell, that was used to create the initial latent image (b) Schematic of the the aerial image intensity from a phase only mask that was subsequently overlaid \((A(X,Y))\). In the aerial intensity images, the lighter regions represent higher exposure intensity (c) Schematic of a grating with space variant duty cycle that was obtained as a result. The local duty cycle is a function of the local dose. The duty cycle at the center of the unit space variant grating cell is the largest and decreases radially in concentric circles across the element.

The space-variant guided mode resonance filter fabrication was performed as follows. A 230nm thick Silicon Nitride layer followed by a 230nm thick Silicon Oxide layer were deposited using plasma enhanced chemical vapor deposition (PECVD) on a fused silica substrate. The wafer was removed from the growth chamber and positive tone Shipley 1805 photoresist was spun-coated to a thickness of 400nm. A binary hexagonal grating pattern with a lattice of 2.30\( \mu \)m was exposed in the photoresist, and using the pattern-shifting multiple exposure technique, the hexagonal unit cell lattice was halved to 1.15\( \mu \)m [18]. The overlay exposure was subsequently carried out using the desired phase-only mask. The resist was developed resulting in a binary grating with uniform radial variation in duty cycle. The gratings were transferred into the 230nm thick Silicon Oxide layer using CHF\(_3\)/O\(_2\) plasma dry etching chemistry. On the same wafer, binary grating structures were patterned without duty.

\[
L(d(X,Y)) = (U(x,y) \otimes \text{comb}(x,y;X,Y)) + A(X^n,Y^m) \tag{1}
\]
cycle variation, in order to baseline the optical performance of the filter in the absence of a duty cycle modulation.

**Results and discussion**

SEM images of the fabricated unmodulated GMR filter are shown in Fig. 6(a). The inset shows a close up of the hexagonal grating structure patterned using the pattern-shifting multiple exposure method.

The diameter of the patterned holes was measured to be 552 nm, with a lattice constant of 1.15 μm. These feature sizes were achieved by using a dose less than optimal. The grating when exposed optimally was designed to provide a patterned feature size of 800 nm. For this feature size, simulations indicated that the filter would provide a reflection peak at 1557 nm with a spectral linewidth of 3nm. The performance of the guided mode resonance filter was measured experimentally using a collimated beam with a 160μm waist from a tunable laser. The measured spectral response is shown in Fig. 6(b). The resonant peak was located at 1559 nm, and had a 5.6 nm linewidth. SEM images of the fabricated modulated GMR filters, with variable duty cycle unit cells, are shown in Fig. 7(a).

The feature size variation was approximately linear, though quadratic intensity profiles were used in the overlay exposure. This was a result of the non-linear dependence of

![Fig. 6. (a) SEM image of the fabricated hexagonal cell GMR structure, with a constant duty cycle. (b) Corresponding measured spectral reflection from the device.](image)

![Fig. 7. (a) Duty cycle variation as a function of spatial location from the center of the GMR grating. (b) Spectral measurement of the GMR filter with duty cycle variation](image)
patterned duty cycle upon total exposure dose. The diameter of the holes at the center of the space variant filter was 650 nm, and increase radially to 750nm towards the device edges. On the 1.15 µm lattice GMR hexagonal-cell layout, this corresponds to a duty cycle variation from 0.43 at the center of the space variant GMR to 0.37 at the edge. The range of duty cycle variation was chosen to be narrow to obtain smooth variation in the spatial reflection profiles. Large variations in the duty cycle will result in discrete dips in the spatial transmission/reflection. Different duty cycle variations can be reliably fabricated using the fabrication method. The measured spectral reflection of the modulated GMR filters is shown in Fig. 7(b). The peak of the resonance was located at a wavelength of 1552.4 nm. For a filter with constant duty cycle, this peak location corresponds to a patterned diameter of 650nm. As mentioned before, this was the feature diameter measured at the center of the space variant the hexagonal cell GMR filter. The side lobe suppression was 10dB and the linewidth was 9nm. This was wider than that obtained for the filter with no duty cycle variation, because the designed duty cycle variations in the space variant device weaken the nominal resonance.

Fig. 8. (a) Schematic of the optical setup for reflected beam profile measurement. The output of the tunable laser coupled to a fiber with a pigtailed collimator was incident upon the GMR based space variant reflector. The reflected beam was directed to a CCD camera by a beam splitter. (b) Schematic of the test setup for transmitted beam characterization. The space variant GMR was placed close to the collimated output from the tunable laser to minimize beam diffraction. Transmitted beam profiles were imaged onto a CCD camera.

The spatial beam profiles were characterized experimentally by imaging the reflection and transmission from the space variant filter at discrete illumination wavelengths as shown in Fig. 8(a). A tunable laser that had an operating wavelength range from 1520nm to 1630nm
was used as the source. The laser output was coupled to a single mode fiber that had a pigtailed collimator, which provided a collimated output beam. The reflection images were obtained by placing a beam splitter in the beam path before the space variant GMR mirror. As a result, the propagation distance to the mirror was ~1cm and the beam was 400µm wide when incident on the filter. The device was illuminated at the measured resonant wavelength of 1552.4nm. A part of the reflected light was re-directed to an imaging port by the beam splitter and imaged on to a CCD camera. The reflected light propagated 6.2cm from the space variant mirror surface to reach the detector plane of the CCD camera.

The reflected beam profile from the space variant mirror was measured at the resonant wavelength. The beam profiles were expected to match those obtained from a linear duty cycle variation across the aperture, as shown in Fig. 4(c), since the fabricated variation duty cycle was approximately linear. However, the propagation of the incident beam and of the reflected beam from the device to the detector was expected to modify the measured beam profiles from those existing close to the space variant mirror element. The diffraction of the incident Gaussian beam due to propagation was determined experimentally by replacing the space variant GMR mirror with a broadband planar dielectric mirror at the same location. The results are summarized in Fig. 9(a). The diffraction of the reflected beam obtained from simulations and the incident Gaussian beam was determined using the Rayleigh-Sommerfield diffraction integral. As shown in Fig. 9(b), the reflected beam profile was significantly modified after propagation compared to the corresponding curve shown in Fig. 4(c). However, the reflected beam from the space variant mirror agrees well with the simulated beam profiles when the beam diffraction due to propagation was included. The reflected beam from the GMR mirror has a wider spread compared to the Gaussian beam reflected from the dielectric mirror as expected.

![Fig. 9. (a) Measured profiles of the Gaussian beam and beam reflected from the space variant GMR mirror when illuminated at the resonant wavelength. The reflected beam profile was significantly modified due to the propagation. (b) Simulated profiles of the Gaussian beam and the reflected beam at resonance from the space variant GMR mirror after propagation to the detector plane.](image)

In order to further characterize the device and comprehensively compare to the simulated results, the transmitted beam profiles through the space variant mirror were characterized. The device illuminated using a collimated beam with a beam waist of 160µm placed 3mm away using the setup shown Fig. 8(b). The measured transmission beam profiles at different illumination wavelengths below resonance, at resonance and above resonance were imaged on to the CCD placed 1.5cm away are shown in Fig. 10. The measured Gaussian beam waist was larger at 320µm due to this propagation. At each wavelength, the transmitted power was measured using a power meter. A flat top profile with a 1.5% dip in transmission at the center was obtained below resonance (Fig. 10(b)), which compares well with the 2% dip predicted by the simulations. At this condition, the measured power transmitted through the device from
the input beam of 300µW was found to be 156µW. At resonance, the central null had a transmission dip of 11% (Fig. 10(c)). The simulations predicted a 15% dip in transmission. This deviation was attributed to the wider spectral resonance resulting in reduced suppression of the incident wavelength by the adjacent spatial regions. The measured transmitted power was 120 µW corresponding to the increased reflection from the space variant GMR. The apodized Gaussian profiles were measured above resonance (Fig. 10(d)). The transmitted power at this condition was measured to be 150 µW. Wavelength-dependent spatial transmission and reflection profiles were obtained from the space variant guided mode resonance filter based mirror element and the experimental measurements agree well with the predicted values.

Conclusions

Guided-mode resonance filter elements with space-variant reflection profiles were designed and demonstrated. The variable reflection profiles were generated by modulating the duty cycle of the 2D grating layer of the GMR with a novel multiexposure technique, thus providing a continuous gradient across the structure. While this results in a broader reflection spectral peak, predictable wavelength-dependent reflection profiles were achieved. The experimentally measured values correspond closely with the model simulations. These elements represent novel space variant spectral mirrors that can be applied to spatial beam shaping and transverse mode control in high energy laser cavities since they are constructed purely with low loss dielectric materials. Moreover, the added spectral variations combined with the spatial control may provide for other novel applications in computational imaging and sensing. Additional features for polarization filtering can also be incorporated into the
structure to make a more robust filtering technique for more complex cavities or imaging systems.

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