Two-dimensional diffraction gratings for use with far-field superlenses

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Abstract: Far-field superlenses (FSLs) allow a new type of optical microscopy that can resolve features below the diffraction limit. Such remarkable resolution is achieved by encoding sub-wavelength features in Moiré patterns, which are produced by diffraction gratings embedded in the FSLs. Typically these diffraction gratings are quasi-one-dimensional structures; this means that the shape and orientation of objects that can be successfully resolved is limited. We investigate two-dimensional grating designs and show that engineering an appropriate grating can lift restrictions on the orientation of the object relative to the diffraction grating. We also describe the impact that grating structure has on the range of spatial frequencies that can be resolved.

Keywords: microscopy; Moiré pattern; sub-wavelength imaging; superlens.


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1 Introduction

Far-field superlenses (FSLs) [1], shown in Figure 1, are able to form superresolved, subwavelength, far field images by combining the near field superresolution of a silver
superlens [2] with the frequency shifting capabilities of a diffraction grating [3]. Provided the period of the grating is chosen appropriately, high spatial frequency, subwavelength patterns will be scattered through the ±1 diffraction orders to lower, propagating spatial frequencies [4]. The original low spatial frequency content of the object spectra, which would otherwise propagate through the 0-diffraction order of the grating, is effectively attenuated by the superlens, which has poor transmission for low spatial frequencies [5]. This means that the high spatial frequency content of the object spectrum can be unambiguously retrieved from Moiré patterns generated by the grating in the far field, so that a super-resolved image can be formed without maintaining intimate contact between the FSL optics and the imaging medium. Note that the low spatial frequency content filtered away by the superlens can be retrieved later via conventional microscopy and can then be added into the super-resolved image during post-processing.

The problem with FSLs is that they have only been demonstrated on one-dimensional, binary objects that have a fixed, known angular orientation relative to the diffraction grating in the FSL [6]. Resolution performance decreases dramatically as the angle between the object and the FSL grating increases past a certain threshold; furthermore, even in the best cases resolution enhancements are confined to one dimension, due to the simple, 1D line gratings used in the FSL. In this paper we investigate the use of two-dimensional diffraction gratings within FSLs to extend their performance to cover objects with arbitrary orientation and to achieve improved resolution simultaneously in more than one dimension.

Figure 1  Schematic of a far-field superlens. Light with a wavelength of 365 nm is incident from the top of the figure on an object in contact with a thin poly(methyl methacrylate) film that protects a slightly thicker layer of silver. The silver enhances the evanescent modes from the object and attenuates the propagating modes. A metallic grating then scatters the evanescent modes into the propagating domain, so that they can be detected at an image plane in the far-field, shown at the bottom of the figure.

2 Method

Object spectra were multiplied with the transfer function of a 10 nm poly(methyl methacrylate) (PMMA): 40 nm Ag superlens that was calculated using the transfer matrix method (TMM) [5,7]. An operating wavelength of 365 nm was used, along with relative permittivity values of $2.3013 + 0.0014 \text{i}$ for PMMA [8] and $-2.7 + 0.27 \text{i}$ for Ag [9]. The dimensions of the silver layer within the superlens was chosen based on prior experimental work [10], while the thickness of the PMMA film was made as small as
practically possible to ensure efficient coupling of evanescent modes from the object to the silver film \[1\].

An ideal, binary grating line profile \[4\] was then used to model the grating in the FSL. The Moiré spectrum produced by the grating and the superlens was then multiplied with a second transfer function, corresponding to a 1 µm thick layer of PMMA. This modelled the projection of the Moiré image from the plane of the grating to an image plane in the far-field. The resultant images were in good agreement with those from a full vector finite element model produced in COMSOL, but required significantly fewer computational resources to produce.

Reconstruction of the original object was performed by shifting parts of the far-field Moiré spectrum into the evanescent domain and artificially adding in the original information contained in the propagating region of the spectrum. Experimentally, this propagating information would normally be captured by a second, diffraction-limited image of the object taken without the far-field superlens present. Different methods for reconstructing two-dimensional objects from Moiré image data were investigated, to assess the feasibility of using FSLs to image arbitrary objects.

3 Results

3.1 Object orientation

The spectrum of a 150 nm period, 1D line grating test object is shown in Figure 2(a), along with superimposed circles that correspond to the propagating part of the spectrum, in the centre of the figure, and the evanescent components of the spectrum that are aliased into the propagating region through the ±1 diffraction orders of the FSL grating, on either side of the propagating circle. Cursory analysis of Figure 2 reveals one of the limiting factors on FSL performance: the orientation of the main spectral line of the object depends on the angle between the object features and the FSL grating, which is set to 3° in Figure 2(a). Figure 2(b) shows the same information as in Figure 2(a), but this time the angle between the object features and the grating features is increased to 45°. None of the main spectral line of the object falls within the circles that are aliased by the FSL, so there will be no meaningful resolution enhancement when the object is placed at this particular angle to the FSL. Figure 3 illustrates the relationship between the angle of the object features relative to the FSL grating and the amount of useful spectral information aliased into the propagating domain, measured as the RMS value of the spectral content within the propagating domain after scattering from the FSL.

Figure 3 shows that good performance is achieved for a quasi-one-dimensional FSL grating when the angle between the object and grating is less than 30°. Switching to a two-dimensional square grating opens another window of performance between 60° and 120°, at the cost of lower peak RMS values. Finally, adopting a grating with a hexagonal pattern provides near constant performance for all angles, only interrupted by narrow nulls at 30°, 90° and 150°.

The effect of reducing RMS amplitude in the propagating region can be seen in the insets of Figure 3, which show 2 µm × 2 µm images of 150 nm period sub-wavelength objects imaged by FSLs with differently shaped gratings. Calculating the Michelson
contrast [12] of each of these insets gives values of 0.58 for the image reconstructed from a FSL with the linear grating, 0.45 for the square grating, and only 0.25 for the hexagonal grating.

**Figure 2** Object spectra of a 150 nm period, 1D line grating object with annotations showing the propagating region (centre circle) that is transmitted through the 0-order of a 120 nm period FSL grating. Regions that are scattered into the propagating region by the ±1 diffraction orders of the grating (outside circles) are also shown. The angle between the object features and diffraction grating features is 3° (a) and 45° (b)

**Figure 3** RMS value of information in the propagating circle after scattering vs. angle between features in the object and diffraction grating, for three kinds of grating patterns: linear, quasi-one-dimensional (solid), square (dashed), and hexagonal (dot-dashed). Insets: 2 µm × 2 µm reconstructed real-space images produced from data scattered by different types of grating. In each case the original object is made up of quasi-one-dimensional features with a period of 150 nm and at an angle of 3° to the diffraction grating features (see online version for colours)
3.2 Reconstruction of two-dimensional objects

Reconstructing an image from scattered Moiré patterns involves shifting parts of the Moiré spectrum to undo the scattering introduced by the diffraction grating, before adding in data to the visible circle of the image from a second, conventional, diffraction-limited image of the object [13]. Care has to be taken to ensure that data scattered by the +1 order does not overlap with data from the –1 order, otherwise both sets of data will be lost and the quality of the reconstructed image will be reduced. For 1D line grating objects of known orientation we can make use of the fact that the object spectrum is relatively sparse: we design the diffraction grating to have the ±1 diffraction circles next to the 0-order circle in k-space, as per Figure 2. An accurate image of the object can be reconstructed as the main features in the ±1 diffraction orders do not overlap with each other when they are aliased to the propagating part of the spectrum by the diffraction grating. This is the approach recommended in Liu et al. [1,6].

Figure 4 Object (a, b) and corresponding image spectra (c, d) reconstructed from data scattered by a one-dimensional diffraction grating (left) and a two-dimensional, square grating (right). The periods of the 1D and 2D gratings are 240 nm and 300 nm, respectively. The objects are a 150 nm line grating (left) and a 150 nm square structure (right).
This approach is not well-suited to more general objects, where the k-space locations of significant features are not known ahead of time. In this situation, the spatial frequency of the diffraction grating is reduced to introduce overlap between the ±1 order circles and the 0-order circle in k-space, as per Figure 4(a). This ensures that ovoid-shaped regions within the ±1 diffraction order circles will not overlap with each other when aliased into the 0-order circle. The spectrum of the resulting image that can be reconstructed is shown in Figure 4(c). The maximum spatial frequency that can be reconstructed is reduced in this case compared to the previous example, but the sub-wavelength spectral area that can be reconstructed is increased.

For objects that have significant features in both the horizontal and vertical dimensions, as shown in Figure 4(b), a 2D diffraction grating is necessary to reconstruct an accurate image. Square diffraction gratings allow sub-diffraction-limited details to be retrieved in both the x- and y-directions, but the size of the non-overlapped spectral regions that can be retrieved is much smaller than those produced by a one-dimensional grating, as shown in Figure 4(d). Although better performance can be had by placing restrictions on the shape of the object spectrum [14] or taking multiple images of the object at known angles [13], for a truly arbitrary object the best approach seems to involve using the expected shape and magnitude of the spectrum to disentangle overlapped spectral regions. This problem is the current focus of our ongoing research.

4 Conclusion

We have shown that the super-resolution performance of a FSL can be decoupled from the orientation of the object, at the expense of reduced contrast in the reconstructed image. Furthermore, we have found that the range of sub-wavelength features that can be successfully reconstructed is reduced when a two-dimensional diffraction grating is used in placed of a one-dimensional structure. This suggests that new approaches to interpret overlapping spectral data are necessary in order to expand the abilities of FSLs from imaging one-dimensional objects to imaging truly arbitrary structures.

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References

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