Fabrication of Photon Sieves by Laser Ablation and Optical Properties

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Abstract

In this work, we demonstrate the feasibility and performance of photon sieve diffractive optical elements fabricated via a direct laser ablation process. Pulses of 50 ns width and wavelength 1064 nm from an ytterbium fiber laser were focused to a spot diameter of approximately 35 μm. Using a galvanometric scan head writing at 100 mm/s, a 30.22 mm² photon sieve operating at 633 nm wavelength with a focal length of 400 mm was fabricated. The optical performance of the sieve was characterized and is in strong agreement with numerical simulations, producing a focal spot size full-width at half-maximum (FWHM) of 45.12 ± 0.74 μm with a photon sieve minimum pinhole diameter of 62.2 μm. The total time to write the ± photon sieve pattern was 28 seconds as compared to many hours using photolithography methods. We also present, for the first time to our knowledge in the literature, thorough characterization of the influence of angle of incidence, temperature, and illumination wavelength on photon sieve performance. Thus, this work demonstrates the potential for a high speed, low cost fabrication method of photon sieves that is highly customizable and capable of producing sieves with low or high numerical apertures.

1. Introduction

Diffractive optical elements (DOEs) offer a lightweight, planar alternative to traditional refractive lenses [1] due to their operating on the principles of optical diffraction and interference, unlike standard refractory optics. In 2001, Kipp et.al [2] developed a novel DOE based on the design of the Fresnel Zone Plate called the photon sieve, which consists of a large number of small pinholes arranged on the underlying Fresnel Zones. The diameter of the pinholes, d, can be equal to or greater than the width of the underlying Fresnel zones, w, and this quantity is typically given by the ratio d/w = 1.5, 3.5, 5.5, and so on in order to produce the maximum focal spot intensity, as explained in Kipp’s seminal paper. It was shown that these photon sieves were capable of producing focus spots smaller than their minimum pinhole diameter due to the suppression of higher order diffraction maxima and larger numerical apertures. This property has made photon sieves attractive for applications such as space telescopes to study heliophysics and other astronomical phenomenon [3], improved signal-to-noise ratios in LIDAR systems [4], focusing elements in maskless
photolithography [5], free-space laser communications systems [6], imaging systems [7], and fiber-to-silicon photonics waveguide coupling [8]. Typically, photon sieves are fabricated by UV or electron beam lithography. However, for large area devices, these writing processes can be extremely time consuming and costly. For example, based on electron beam exposure time equations given in [9], using typical beam current and dose parameters of 1 nA and $10^{-3}$ C/cm$^2$, respectively, a 30 mm$^2$ sample, such as the one presented in this work, should take approximately 3.5 days to expose. Laser-based UV lithography is much quicker, but still can take multiple hours to expose areas of several square-cm and requires chemical etching processes. Mask-based lithography is also very fast, but requires a new mask to be fabricated each time even a small change is made to the photon sieve design, and is therefore not ideal for applications with changing design parameters. In addition, all of these techniques require pre and post-exposure chemical processes such as etching.

The implementation of laser ablation to fabricate micro/nano features for photon sieves will mitigate all of these issues, as no chemical processing is generally needed, and the pulsed beams can be scanned at speeds of greater than 1000 mm/s using commercial scan heads. High powered short and ultra-short pulsed lasers have shown great promise in the field of materials processing [10]. It has also been shown that by using ultra-short laser pulses, sub-micron features can be achieved [11]. This is because the effects of thermal diffusion are minimized in shorter pulses [12]. Few hundred nanometer diameter holes have been achieved using NIR lasers [13], and features as small as 82 nm have been reported using soft x-ray sources [14]. Thus, laser ablation techniques have the potential to produce both low and extremely high numerical aperture photon sieves without sacrificing device performance, as we will show, which is especially useful for applications where the photon sieve operating variables (focal length, numerical aperture, wavelength) are often changing, or multiple sieves are used. In addition, the operation tolerances for photon sieves have not been thoroughly examined previous to this work, leaving a gap in understanding for actual integration of photon sieve devices into their applications.

2. Simulation of Photon Sieve Focal Point FWHM and Diffraction Efficiency

Numerical simulations of the photon sieve design were carried out using a custom numerical code adopted from the vector diffraction theory treatment of photon sieves first described by Tang et. al [15]. The photon sieve design used for both simulation and experiment was for operation at 633 nm wavelength, with a focal length of 400 mm and 19 rings. A $d/w$ ratio of 1.53, and a total device diameter of 6.2 mm was used. A simulation was performed to obtain a line profile through the center of the photon sieve focus spot over a length of 150 μm. Data from the same simulation was also used to predict the diffraction efficiency of the photon sieve. In order to model the diffraction efficiency, an integration of the square modulus of the total three-dimensional complex electric field at the focal point was performed to obtain the total optical intensity inside a sphere with radius equal to the $1/e^2$ radius of the focal point. The value of the electric field incident on the sieve was taken to have a magnitude of 1. The code was also used to model the illumination wavelength tolerances of the focal point.
intensity and size, which was done by changing the illumination wavelength of the simulated 633 nm sieve design. The simulated sieve was shown to have a focal point FWHM of 44.59 μm when illuminated with 633 nm wavelength light. The simulated diffraction efficiency was 1.275%.

3. Photon Sieve Fabrication via Laser Ablation

Fabrication of the photon sieve was carried out on soda lime glass substrate coated with 50 nm of silver film via electron beam evaporation. The total optical transmission through the silver layer is approximately 2% of the incident light at 633 nm wavelength. Photon sieve pinholes were formed using a commercial 1064 nm wavelength ytterbium fiber laser (IPG Photonics, model YLP-RA-1-50-30-30) with a pulse width of 50 ns, pulse repetition rate of 20 kHz, and an average output power of 9 W. The laser beam was directed through a beam expander and into a commercial galvanometric scan head (Sino-Galvo, model JD2206) fitted with an f-theta lens, producing a focus spot of approximately 35 μm. The laser and scan head were controlled simultaneously by an external controller (Lanmark Controls, Winlase LAN software and Maestro3000 controller) which reads the design as a vector graphic and scans the beam across the desired substrate areas one line at a time to produce desired features. The line spacing can be selected by the user in the software GUI, and was set to 10 μm for this work. The beam was scanned at 100 mm/s, resulting in one laser shot per micron spacing. A small vacuum nozzle was used above the substrate in order to remove the ablation plume to prevent silver from re-depositing on the photon sieve surface.

4. Results and Discussion

4.1. Photon Sieve Pinhole Morphology

An image of the fabricated photon sieve is shown in figure 1. Because the laser beam intensity distribution at the focus of the f-theta lens is a Gaussian distribution, and due to line-scanning of the laser beam across the substrate to create features, the inner edges of the presented photon sieve pinholes are not perfectly clean circles. The line-by-line scan, coupled with the Gaussian laser intensity seems to cause the edges of the filled features to not fully ablate, due to the edge of the feature receiving ablation energy from beam minimum rather that the center maximum. The effects of this uneven irradiance are shown in figure 2.

When the laser beam is scanned across the substrate, the control software assumes that the incident laser beam focus is a mathematical point positioned on the center of the physical laser spot. This is because beam-scanning software does not account for the size of the beam being scanned; it can only control the scan head mirrors. For example, for a 20 μm laser spot with its center being scanned over a distance of 50 μm, the actual laser spot will irradiate the 50 μm line, plus an additional distance at the beginning and end of a scan line equal to the laser spot radius. Thus, in the above example, a distance of 70 μm is irradiated and therefore subject to larger ablation area. However, the additional spot radius on either side of the mark is only exposed to a fraction of the maximum laser intensity seen by the rest of the scan line, as it is being irradiated by an off-center portion of the laser spot. This discrepancy in
irradiance (and therefore optical energy) of the substrate can cause less material to be ablated from the edges of a scan line or feature, resulting in the marks shown in figure 2.

This effect, however, does not appear to impact photon sieve performance, as indicated by the good agreement between numerical simulations and measured data for the focus spot. Beam shaping optics can be used to produce a flat-top laser intensity profile at the focus of the f-theta lens, which would result in the entire laser mark seeing a constant irradiation intensity, and therefore ablate more uniformly. The use of ultrafast laser pulses such as pico or femtosecond sources could potentially also mitigate the issue without the need for beam shaping optics, as the shorter pulse time can prevent melt formation at the edge of a mark, as explained by Domke et. al [16].

4.2. Characterization of Photon Sieve Focal Spot Size and Efficiency

The fabricated photon sieves were characterized using a Helium-Neon laser illumination wavelength of 632.8 nm and a scanning slit beam profiler (Thorlabs model BP109-VIS) with 1.20 μm resolution placed at the focal point. The collimated testing laser beam was expanded via a Keplerian telescope setup to cover the full area of the photon sieve. A 200 μm aperture was placed between the sieve and beam profiler in order to block out the zero order diffracted light, which resulted in a more simple beam profile measurement. In order to account for the slightly transmissive nature of the Ag thin film, a background measurement was taken by shining the laser light onto the unpatterned silver film and recording the intensity data with the beam profiler. This was done so that this background signal could be accounted for when analyzing the photon sieve performance. A plot of the measured photon sieve focus intensity distribution with background signal subtraction is shown in figure 3 and is compared with the numerical simulation result. The measurement is in very strong agreement with simulation, with measured FWHM values of (45.12 ± 0.74) μm. In the un-subtracted data (not shown), we see a baseline power of approximately 5.5% of the peak value, whereas the subtracted background noise gives essentially zero intensity surrounding the focus spot (less than 1% of the maximum intensity value). Both of these results are consistent with data published in other works, such as Liu et. al [17].

Diffraction efficiency of the photon sieve was also investigated, and is here defined as the ratio of the total power in the focal spot to the total power incident upon the photon sieve. In order to measure this, the beam profiler in the setup described above was replaced by a photodiode and optical power meter. A 200 μm aperture was then placed onto the face of the detector and aligned with the photon sieve focus spot in order to block any light outside of the focal spot, such as the zero order diffracted light, which would otherwise result in an artificially inflated efficiency value. The diffraction efficiency was measured multiple times for consistency, and found to be (1.1995 ± 0.0025)%, which is in strong agreement with simulated values.

4.3. Dependence of Focal Point Characteristics on Angle of Incidence, Illumination Wavelength, and Temperature

It is known that the behavior of diffractive optical elements is strongly tied to angle of incidence. However, the actual influence of incident angle on photon sieve focusing
capabilities, to the best of our knowledge, has not been reported. Therefore it is useful to characterize the angular dependence of photon sieve focal spot size and diffraction efficiency, as it gives insight to alignment tolerances for any potential applications.

In order to characterize the focal point at various angles of incidence, the photon sieve was mounted on a rotational stage and aligned at the different incident angles. Beam profile data was taken at each angle, with the angle being increased by one degree from 0° to 6°, and two degrees from 6° to 30°. This was done to thoroughly characterize the small angle behavior of the photon sieve, as these smaller angular misalignments are more likely to occur than large misalignments in potential applications. The incident laser beam was made to cover the entire photon sieve pattern at every angle, and the sieve was rotated about the y-axis. Data was taken to understand the relative change in FWHM at various incidence angles, as well as the change in relative intensity of the focal point. As is shown in figure 4, the focal point FWHM along the x-axis is fairly constant until 4°, with the focal point expanding approximately one micron per degree. At incident angles greater than 5°, the focal spot quickly and exponentially increases in size with increasing angle. At approximately 13°, the focal point had doubled in size, and by 20° had tripled and was no longer Gaussian in shape. The expansion of x-axis FWHM at increasing angles of incidence follows an exponential dependence, as shown in figure 4. The deviations from the fit curve at larger incidence angles can be attributed to the focal point instability at these large angles. The y-axis FWHM remained fairly unchanged, expanding by only 3 microns at an incidence angle of 20 degrees. As a result, rotation of the photon sieve about the y-axis resulted in a stretched focal point along the x-axis.

Focal point intensity along the x-axis was also greatly affected by increasing angle of incidence. A plot of the relative focal point intensities is given in figure 5. Again, the photon sieve is fairly tolerant with angular misalignment up to 4°, but performance is quickly diminished at larger angles, with focal point intensity dropping to 80% of the normal incidence value at 10°, and to roughly 50% at 15°. This drop in intensity can easily be explained, since when the sieve pinholes are rotated about the y-axis the effective area of the pinhole is reduced by the cosine of the angle of incidence, resulting in a lower photon flux through each pinhole. More interesting is the slight increase in intensity at small angles (less than 5°). To corroborate the validity of this result, these measurements were taken on the presented sieve several times. Measurements were also taken on a 150 mm focal length photon sieve fabricated using the same system. The results were consistent across all measurements of both devices, and all showed an intensity increase at small angles of incidence. Raw images of the beam profile at various angles of incidence are shown in figure 6.

As with FWHM measurements, the y-axis intensity profile was largely unchanged with sieve rotation about the y-axis. From this we can ascertain that sieve rotation about an axis results in a change in focal point characteristics along the opposite axis. It has been shown here that photon sieves are relatively stable under small angular misalignment, but performance rapidly degrades at incident angles greater than 4°.
Simulations and measurements were also carried out to evaluate the photon sieve performance as a function of illumination wavelength in order to better understand the photon sieve effective bandwidth. Findings regarding FWHM and peak intensity are summarized in figure 7, and measured values in the table are denoted as such. Data was simulated for wavelengths of 633, 636.57, 638.37, 640, 646, and 653 nanometers. Measured values for off-design wavelength FWHM and intensity were taken using laser diodes operating at 636.57 nm and 638.37 nm, as measured by a spectrometer. It is known that photon sieves with $d/w < 2.4$ do not possess strict tolerances to illumination source linewidth [2], so the slightly larger linewidth of the laser diode compared to the 632.8 nm Helium-Neon laser source should not affect sieve performance for this measurement. The elliptical diode output beam was collimated using an aspheric lens and made circular by an anamorphic prism pair. It was then passed through a spatial filter and re-collimated prior to illuminating the photon sieve. As is seen in figure 7, focal point intensity quickly degrades with deviation from the design wavelength. FWHM is more tolerant to small deviations, but increases quickly at $\Delta \lambda > 7 \text{nm}$. Simulated values agree well with experimental data.

Lastly, data was gathered to understand the temperature dependence of focal point characteristics to assess the normal operating temperatures that are encountered in different real applications. In order to do so, the photon sieve was placed in a mount that allowed for free expansion of the substrate in the x and y directions. This was done so as to not force the photon sieve into maintaining its structural shape as well as to prevent cracking of the substrate. The photon sieve was heated from the glass side using a heat gun, and the temperature was monitored using a thermocouple attached to the silver film side of the photon sieve near the pattern, and was fixed to the silver with aluminum tape to ensure good thermal contact. Measurements were taken from room temperature (24 °C) to 100 °C in 10 °C increments. The photon sieve was heated to the desired temperature and maintained at that temperature while beam profile measurements were collected, in order to guarantee stability of the temperature. A summary of FWHM and peak intensity characteristics are shown in figure 8. There was little to no variation seen in focal point characteristics of the photon sieve at elevated temperatures, with 3.2% maximum variation in FWHM values (1.5 μm variation) and 10.5% maximum variation in focal point intensity. This demonstrates the consistency of rigid-substrate photon sieve performance at elevated temperatures.

### 5. Conclusion

We have successfully demonstrated the fabrication of photon sieve lenses via laser ablation process. A photon sieve of 400 mm focal length and area of 30.22 mm$^2$ was fabricated by means of a nanosecond-pulsed ytterbium fiber laser. The total time to pattern the photon sieve lens was 28 seconds only, and the use of high power and/or shorter pulse lasers would decrease this time even further. Photon sieve performance has a fair tolerance for pinhole morphology. Despite imperfections in the partially ablated regions near pinhole edges, photon sieves performed very similarly to the simulated values. The differences between measured and simulated FWHM and diffraction efficiency were 1.18% and 5.96%, respectively. The performance of photon sieves under various angles of incidence was characterized and small angle tolerances exist for most purposes, with limited change in FWHM and focal point intensity at angles less than 4°. Illumination wavelength tolerance
was also simulated, measured, and presented. FWHM values are fairly stable when the photon sieve is illuminated by light within a few nanometers of the design wavelength, but increases rapidly at greater than 7 nm $\Delta \lambda$. However, the intensity of the focal point drops by a factor of 4.5 within this same 7 nm range, with greater reduction in intensity seen at larger $\Delta \lambda$ values. Based on the work presented here, we conclude that high quality, high performance photon sieves with large or small numerical apertures can be rapidly and reliably fabricated via laser direct writing, resulting in a reduced fabrication time and cost of photon sieves for various research and industrial applications.

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Fig. 1.
SEM image of the laser fabricated photon sieve.
Fig. 2.
SEM image of photon sieve pinhole edge morphology. Characterization results suggest that the imperfections as explained above do not affect device performance.
Fig. 3.
Simulated and measured photon sieve focal point x-axis intensity profiles (normalized).
Fig. 4.
Plot of the relative change in x-axis FWHM vs. angle of incidence.

\[ y = 0.8354e^{0.0699x} \]
Fig. 5.
Plot of the relative change in focal point intensity vs. angle of incidence.
Fig. 6.
Images of focal point showing 2D intensity profile at different angles of incidence (a) 0°, (b) 4°, (c) 10°, and (d) 25° (Intensity scale at far left of image).
Fig. 7.
Effect of illumination wavelength on focal point properties.
Fig. 8.
Photon sieve performance at various temperatures.