High spatial resolution measurement of volume holographic gratings

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ABSTRACT

The conventional approach for measuring volume holographic gratings typically requires measuring the transmitted and diffracted beams simultaneously while varying the angle of incidence. To obtain the spectral response a tunable laser is used with a fixed angle of incidence. In the former case, the motion of the diffracted beam from reflection gratings requires the detector to move with it, or otherwise the range of angles must be limited. Furthermore it is often difficult to separate the diffraction from the specular surface reflections, increasing the error of the measurement. In the latter case, a high cost tunable laser is required.

We describe methods for the measurement of volume holographic gratings with high spatial resolution. A fixed wavelength laser in conjunction with a high-resolution digital camera is used to measure the angle selectivity of the transmitted beam only. The measured data are fit to a model of the grating diffraction combined with the cyclical interference from the surface reflections in order to increase the accuracy when measuring uncoated gratings. The system is capable of simultaneously measuring diffraction efficiency, loss, surface reflectivity, Bragg angle, and grating tilt in one plane, with a resolution of better than 250 micrometers over the area of a 45 mm by 35 mm wafer. Through a transformation utilizing the de-phasing term of the coupled wave analysis of thick hologram gratings, the wavelength selectivity is also obtained.

Keywords: volume holographic grating, narrow linewidth filter

1. INTRODUCTION

Volume holographic reflection gratings have been shown to be an extremely accurate and temperature-stable means of filtering a narrow passband of light from a broadband spectrum. This technology has been demonstrated in practical applications where narrow full-width-at-half-maximum (FWHM) passbands are required. Furthermore, such filters can be designed to have arbitrary wavefront curvatures, center wavelengths, and output beam directions.

Holographic recording can be performed with thin or thick media. When the material in which the hologram is present is thick, then Bragg selectivity occurs.[1] Photorefractive materials, for example LiNbO3 crystals and certain types of polymers and glasses, have been shown to be effective media for storing volume holographic gratings with high diffraction efficiency and storage density. They are used in applications such as optical filtering,[2] holographic optical memory,[3,4] image processing,[5] and others. In addition, volume gratings Bragg-matched to reflect at normal incidence have been used successfully to stabilize and lock the wavelength of semiconductor laser diodes.[6]

For the economical mass production of volume holographic gratings, testing methods must be used which are accurate, fast, and easy to use. The conventional approach for measuring volume holographic gratings typically requires measuring the transmitted and diffracted beams simultaneously while rotating the grating. The motion of the diffracted beam requires the detector to move during the test or an imaging system be used. Otherwise the range of angles is limited due to the size of the detector. Furthermore it is often difficult to separate the diffraction from the specular surface reflections, increasing the error of the measurement. With a single detector element, the spatial resolution of the data is also limited. To obtain the spectral response a tunable laser can be used with a fixed angle of incidence. While allowing for a simpler optical system, a high cost tunable laser is required.

We describe methods for the measurement of volume holographic gratings with high spatial resolution and speed. A fixed wavelength laser in conjunction with a high-resolution digital camera is used to measure the angle selectivity of the transmitted beam only. The measured data are fit to a model of the grating diffraction combined with the cyclical interference from the surface reflections in order to increase the accuracy when measuring uncoated gratings. The system is capable of simultaneously measuring diffraction efficiency, loss, surface reflectivity, Bragg angle, and grating tilt in one plane, with a resolution of better than 250 micrometers over the area of a 45 mm by 35 mm wafer. Through a transformation utilizing the de-phasing term of the coupled wave analysis of thick hologram gratings, the wavelength selectivity is also obtained.

2. CONVENTIONAL METHODS

Figure 1 illustrates a basic non-slanted volume holographic reflection grating readout at an angle θ. When the Bragg condition, $\lambda_r=2n(\lambda_r)\Lambda\cos(\theta_r)$, is satisfied the grating will most efficiently diffract the incident beam, where λ_r is the readout wavelength in vacuum, $n(\lambda_r)$ is the refractive index of the volume holographic grating element material at the readout wavelength, Λ is the grating spacing, and θ_r is the readout angle of incidence inside the material. For a simple uniform grating, the characteristics are completely determined by the thickness of the volume element, the refractive index modulation depth, the grating spacing, and the slant angle relative to the surface normal.

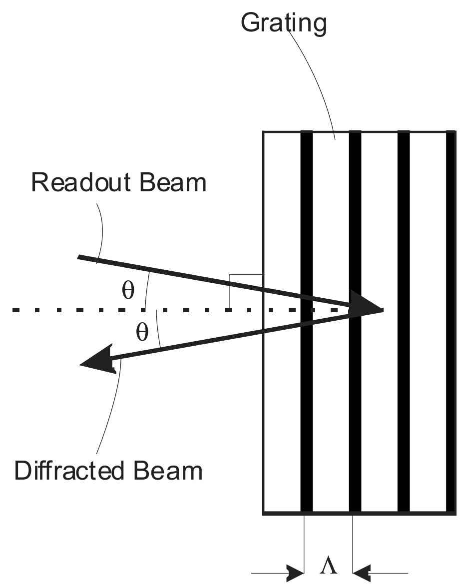

Figure 1: A simple unslanted volume holographic grating with period Λ.

Figure 2 shows a typical measurement system that uses a collimated laser as the readout source. Both the transmitted and diffracted beams are measured with separate detectors as the angle between the incident beam and the part under test is varied. The diffraction efficiency, grating spacing, in-plane grating tilt angle, and loss can be measured with this type of system. By relocating the diffracted beam detector, transmission gratings can also be measured.

The spatial resolution of this approach is limited by the size of the readout beam, and the measured performance is averaged over that area. Since it is desired to measure the grating performance with plane wave illumination, the readout beam cannot be made small. With a large readout beam, spatial variations in the performance of the grating cannot be discovered. These variations could be the result, for example, of material defects, variation in material photosensitivity, or disturbances during recording. Increasing the area of coverage is possible by scanning a small beam over the larger grating, however this is a time consuming process and increases the complexity of the system by adding two additional axes of motion.

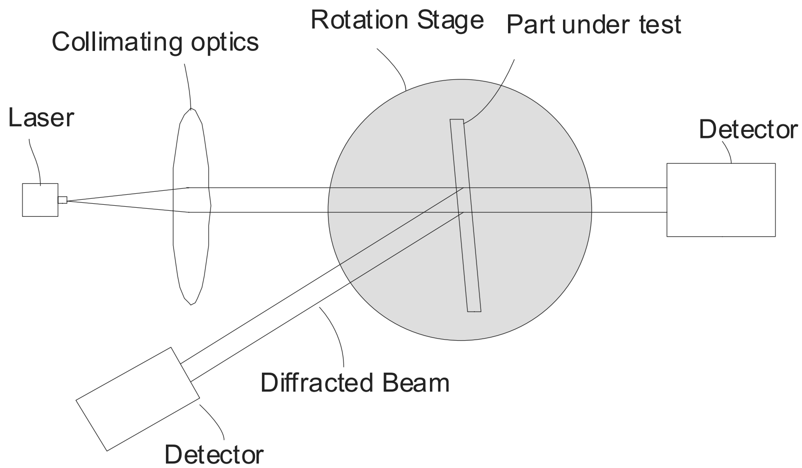

Figure 2: The conventional approach to measuring volume holographic reflection gratings.

An alternative approach replaces the fixed wavelength laser in Figure 2 with a tunable-wavelength laser and dispenses with rotation of the wafer. The laser is then tuned through the Bragg peak to measure the peak diffraction efficiency. While this eliminates one axis of motion, and depending on the properties of the tunable laser and detectors could be faster, such an approach cannot be used to determine the grating tilt angle.

3. HIGH RESOLUTION METHOD

For mass production of volume holographic grating elements it is desirable to measure the grating characteristics at the wafer level before dicing into final parts of smaller size. Figure 3 is a schematic diagram of a high-spatial-

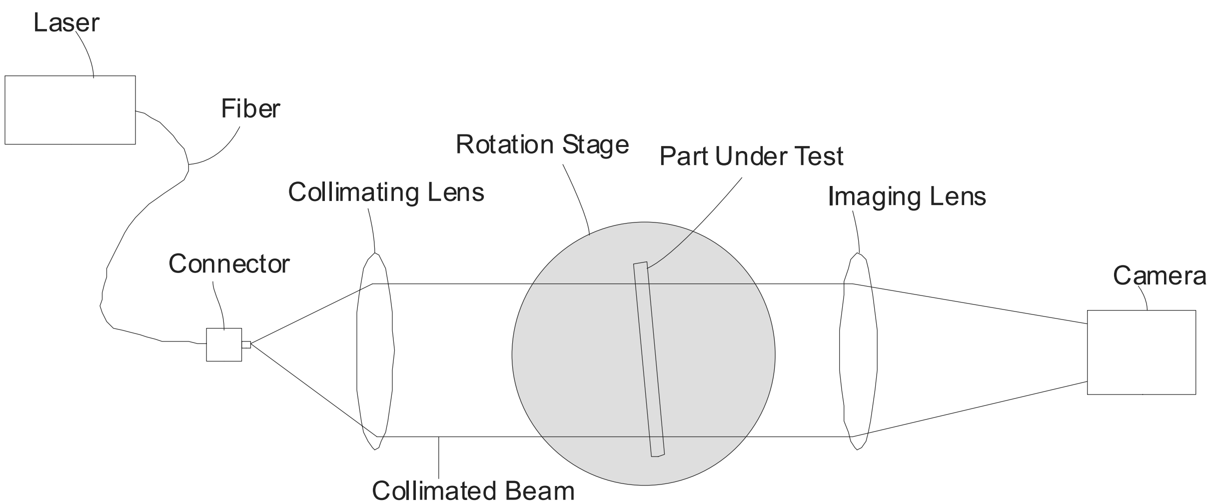

Figure 3: High-resolution volume holographic measurement system.

resolution volume hologram measurement system. A source laser with a fixed wavelength is fiber coupled, terminated with a fiber connector, and collimated. This allows the wavelength to be easily changed in the system without realigning the optics. The collimated beam passes through the wafer being tested. The beam transmitted through the wafer is imaged with a lens to the 2-d camera sensor. The part under test is mounted on a rotation stage with a rotation axis that is centered within the measurement beam. The spatial resolution of the system is primarily limited by the performance of the imaging system and the sensor array.

In this system the laser wavelength is fixed and the readout angle is varied to measure the Bragg-matching angle and the Bragg-matched diffraction efficiency. For a general reflection grating the maximum diffraction efficiency occurs when the Bragg-matching condition is satisfied, given by

$$\lambda_b = 2n\Lambda\cos(\phi - \theta_b), \quad (1)$$

where λ_b is the measurement wavelength, n is the refractive index of the grating element (at the measurement wavelength), Λ is the grating spacing, ϕ is the grating tilt angle, and θ_b is the angle of incidence measured inside the media.

From energy conservation, and assuming a perfectly anti-reflection coated part, the system must obey the relation $P_i = P_d(\theta) + P_t(\theta) + P_l$ where θ is the incident angle, P_i is the incident power, P_d is the diffracted power, P_t is the transmitted power, and P_l is the power lost due to absorption and scattering, assumed to be independent of incident angle. The incident power P_i is first measured directly without the wafer in place. By inserting the wafer and placing it in a configuration that is far from the Bragg-matching condition, such as choosing a suitable incidence angle, the loss can be measured. Under these conditions P_d is assumed zero, and with the measured value of P_{t0} the lost power is computed as $P_l = P_i - P_{t0}$. Once P_i and P_l are known, P_t is measured and P_d is computed as $P_d(\theta) = P_i - P_l - P_t(\theta)$ for various incident angles. The external diffraction efficiency of the grating when Bragg-matched is taken as the maximum diffracted power measured over a range of angles that includes the Bragg matching angle, θ_b, divided by the incident power:

$$\eta_{ext} = \frac{P_d(\theta_b)}{P_i}. \quad (2)$$

With this system the grating spacing and slant angle can also be determined from the same measurement. If θ_{b1} and θ_{b2} are the two angles (inside the media) that satisfy the Bragg matching condition, then the slant angle is

$$\phi = (\theta_{b1} + \theta_{b2})/2. \quad (3)$$

The grating spacing is then

$$\Lambda = \lambda_b \frac{\cos(\phi - \theta_{b1})}{2n}. \quad (4)$$

Equation (2) was derived with the assumption that the loss is independent of angle. However when there is a significant amount of loss, that is not true. For a strong grating, the effective distance propagated through the media by the diffracted beam is not the same as the thickness of the media. This can be taken into account by applying the coupled wave analysis provided in reference 1.

Figure 4 is a plot of the internal diffraction efficiency and grating slant angle measured with this system. It has 160mm resolution over a 45 mm by 35 mm area. Additionally, the surface reflectivity, normal-incidence Bragg wavelength, and bulk transmission are also obtained.

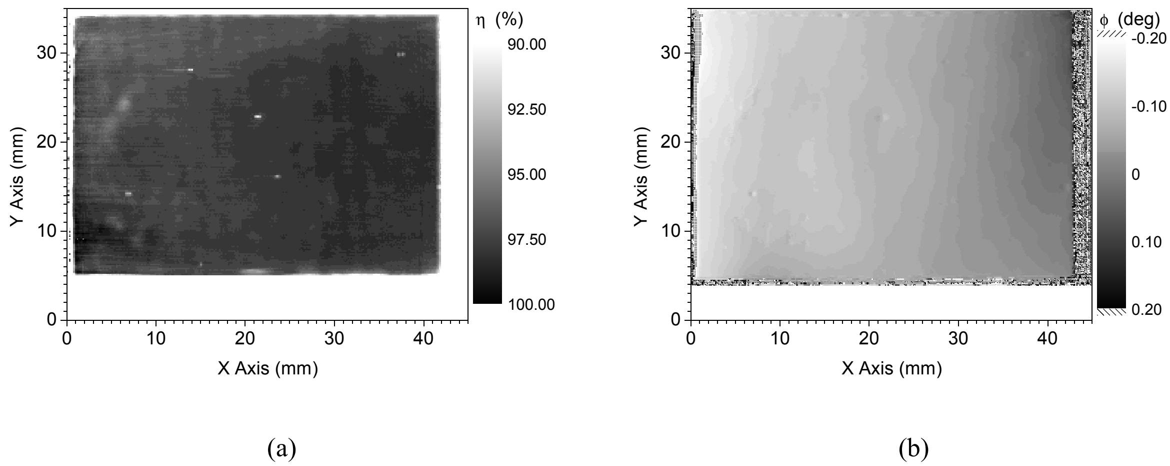

Figure 4: (a) Internal diffraction efficiency, (b) Grating slant angle.

For parts that are not anti-reflection coated there is interference between reflections from the two surfaces which must be taken into account in order to increase accuracy. The amplitude of the intensity modulation created by this interference generally approaches 8% depending on the refractive index. Figure 5 illustrates the case considering the

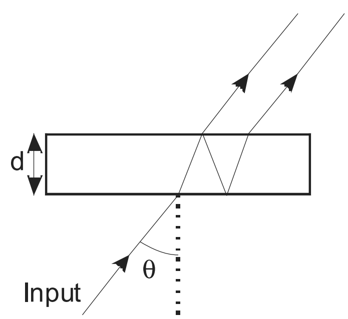

Figure 5: Illustration of the primary and first reflected beam through a parallel window with an input angle of θ.

primary transmitted input and the first reflected beam in a parallel window. As the input angle varies the relative phases between the primary and first reflected beam changes, causing the transmitted intensity to be modulated according to the equations

$$t(x,y,\theta)=t_0\left[1+m\sin\left(\Delta\phi(\theta)+\phi_0(x,y)\right)\right], \tag{5}$$

$$t_0=T(1-R)^2\left(1+(RT)^2\right), \tag{6}$$

$$m=\frac{2RT}{(RT)^2+1}, \tag{7}$$

$$\Delta\phi=\frac{4\pi d}{\lambda}\sqrt{n^2-\sin^2(\theta)}, \tag{8}$$

where θ is the input angle, x and y are positional coordinates, t_0 is the average transmission, R is the single surface reflectivity, T is the bulk transmission, m is the modulation degree, ϕ_0 is a constant phase factor, and $\Delta\phi$ is the phase difference at a particular angle between the primary and first reflected beams.

The measurement data is used to determine t_0, m, and ϕ_0 by numerically fitting equation 5 with them as free parameters. Using equations 6 and 7 it is then possible to compute R and T as

$$T=\frac{p}{2}+\sqrt{\left(\frac{p}{2}\right)^{2}-\gamma^{2}}\,, \tag{9}$$

$$R=\frac{\gamma}{T}\,, \tag{10}$$

where $\gamma=\frac{1-\sqrt{1-m^{2}}}{m}$ and $p=2\gamma+\frac{t_0}{1+\gamma^{2}}$. For small angle ranges the reflectivity can be assumed to be constant.

When measuring a volume holographic grating, the angle range is chosen well beyond the Bragg-angle in order to obtain data unaffected by the grating. Figure 6 shows the transmitted beam values measured for several positions of a grating. The modulation from the surface reflections is clearly evident. In the center of each scan a slight perturbation of the oscillation is seen, which is extra loss from the grating diffraction. The left one-sixth and right one-sixth of the data is used to fit the function of Equation 5, where there is negligible influence from the grating. The fit function is plotted over the entire range as the solid line.

The data in the area of the grating is the sum of the grating response and interference from the surface reflections. In the case of relatively weak gratings, below about 5 times the single surface reflectivity, it is difficult to obtain an accurate value for the grating's diffraction efficiency. By subtracting the fit function from the measured data and normalizing by the incident power, the diffraction efficiency can be obtained, as shown in Figure 7 for several positions. Here the solid line is a direct measurement of the diffracted beam in a system similar to that of Figure 2, and the cross marks are values obtained from the data and fit shown in Figure 6. The oscillation is suppressed and the grating's angle selectivity is now clearly visible.

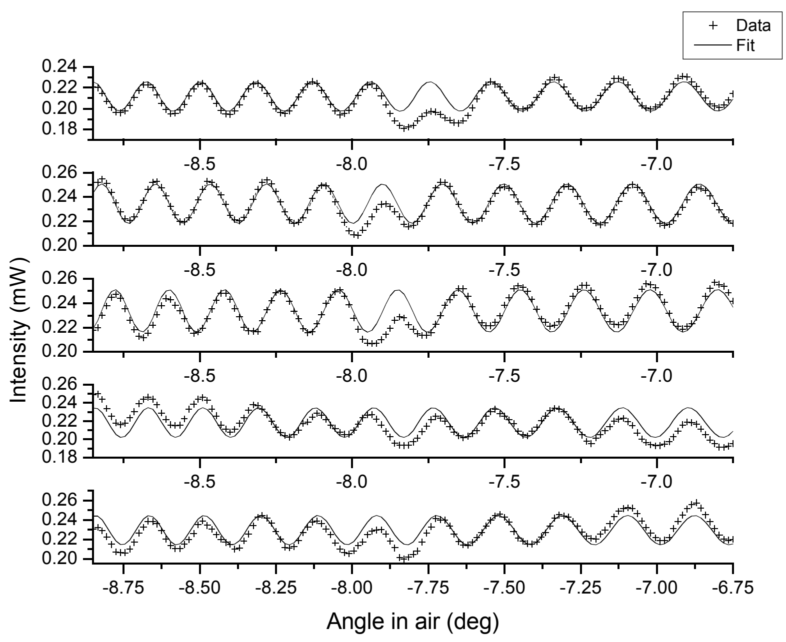

Figure 6: Data collected for several positions of a volume holographic grating (crosses) and the fit to the surface reflection induced oscillation (solid line).

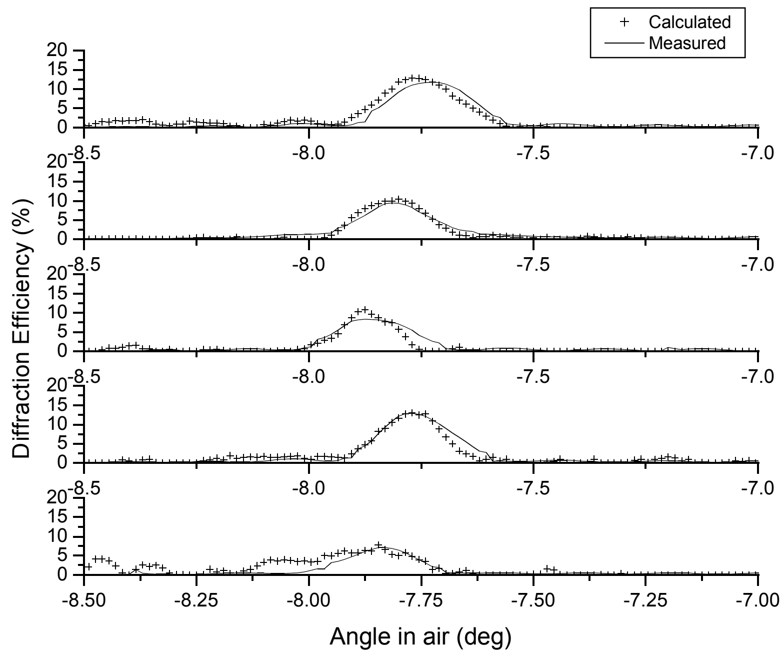

Figure 7: Angle selectivity data measured (solid line) directly from the diffracted beam compared to that calculated (crosses) from measurements of the transmitted beam only and plotted in Figure 6.

It is feasible to obtain the grating's wavelength selectivity from the measurement of its angle selectivity. It requires application of the de-phasing measure, ϑ, from the coupled-wave analysis,[1] reproduced here for convenience:

$$\vartheta = \frac{2\pi}{\Lambda}\cos(\phi-\theta) - \frac{\lambda\pi}{n\Lambda^2}\ . \tag{11}$$

The de-phasing parameter for a wavelength mismatch is

$$\vartheta(\lambda=\lambda_{bs}+\Delta\lambda,\theta=\theta_{bs}) = \frac{\Delta\lambda\pi}{n\Lambda^2}\ , \tag{12}$$

where λ_{bs} is the Bragg wavelength producing a Bragg angle of θ_{bs}, from Equation 1. Likewise for an angle mismatch, and using Equation 1

$$\vartheta(\lambda=\lambda_{bm},\theta=\theta_{bm}+\Delta\theta) = \frac{2\pi}{\Lambda}\left|\cos(\phi-\theta)-\cos(\phi-\theta_{bm})\right|\ , \tag{13}$$

where λ_{bm} is the wavelength that gives a Bragg angle of θ_{bm}. For an unslanted reflection grating with a Bragg angle θ_{bs}=0, setting Equations 12 and 13 equal and solving for λ yields

$$\lambda = \frac{\lambda_{bm}}{\cos(\theta_{bm})}\left(1 \pm \left|\cos(\theta)-\cos(\theta_{bm})\right|\right)\ . \tag{14}$$

Here the positive holds for $|\theta| > |\theta_{bm}|$ and the negative for $|\theta_{bm}| > |\theta|$.

Figure 8 shows angle selectivity measurement data for a grating readout at 1534 nm. The angle dimension was

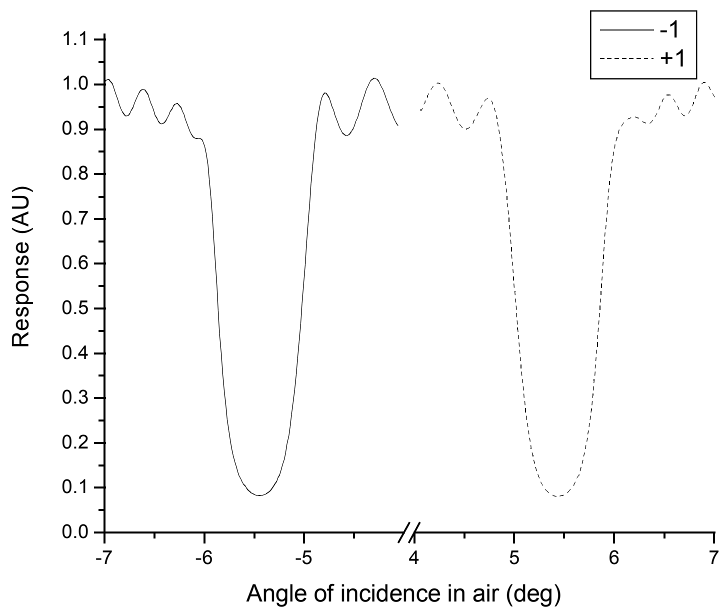

Figure 8: Angle selectivity measurements with a readout wavelength of 1534 nm.

transformed with Equation 14 and is plotted in Figure 9 alongside a direct wavelength scan at normal incidence, utilizing a tunable laser. There is a reasonable agreement between the two sets of data.

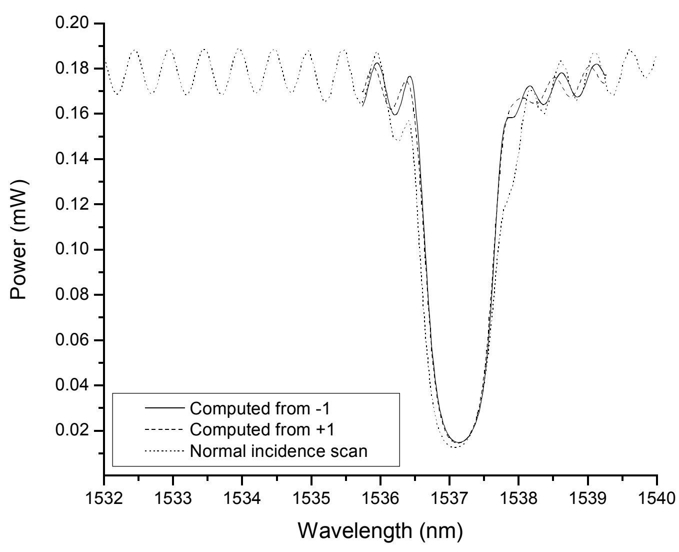

Figure 9: Wavelength selectivity generated by coordinate transformation from angle to wavelength utilizing Equation 14 compared with a direct wavelength scan with a tunable laser at normal incidence.

4. CONCLUSION

The system presented has proven effective at quickly characterizing volume holographic gratings. The process of measuring only the transmitted beam has simplified the system design and enabled the use of a sensor array, allowing large, well-collimated, beams to be used while still obtaining high-resolution data. Additionally, methods have been developed for measuring relatively weak gratings in uncoated parts, and for transforming the angle-selectivity data gathered into the grating's wavelength response.

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