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MEASUREMENT OF OPTICAL DIFFRACTION BY WAVELENGTH-SIZED SLITS

by

William E. Haller

Memorandum No. UCB/ERL M88/37

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Title

RESEARCH PROJECT

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Measurement of Optical Diffraction by

Wavelength-Sized Slits

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ABSTRACT

Diffraction by small open lines in chrome (slits) has been measured and the data compared to scalar diffraction theory. The measurement system consists of a chopped HeNe laser illumination, a mask held by a translational and rotational stage, and a photomultiplier tube on a revolving arm connected to a lock-in amplifier under the control of an IBM PC XT computer. Results for slits down to a wavelength in size show transmission nearly proportional to slit size and only slight polarization effects. Initial plots of total transmitted power divided by slit size showed a decrease for small slits. However, correcting for mask bias and/or edge roughness improves agreement with rigorous electromagnetic theory.

1. INTRODUCTION

In optical lithography projection printed images of both desired device features and undesired defects on the order of a wavelength in size are becoming a concern. As feature size is reduced the amount of light transmitted decreases and the patterns into which it is diffracted broadens; in addition polarization effects occur. How this impacts the use of 1x masks down to 0.25 um at 248 nm can be assessed by simulation programs such as SAMPLE[1]. However, the limits of the current scalar diffraction model must be examined. While there are many rigorous and numerical analyses in the literature, direct measurement of the actual scattering with all the imperfections of the mask is most appealing.

Measurement of diffraction by small slits has been undertaken before[2,3] but not specifically for chrome masks as used in optical projection printing. An exact solution of diffraction by a slit in a thin conducting screen of electromagnetic (vector) waves is available[4] as well as a variational solution[5]. These rigorous solutions provide guidance for the measurements here which seek to determine the limit of the much more tractable scalar diffraction approach. The model employed for analysing data collected is that for diffraction of a scalar wave by a slit in a thin screen[6], and provides a reasonable fit to the data. The scalar model predicts total transmitted power will vary in direct proportion to the width of the slit, and naturally does not exhibit any polarization effects. It is the departure of measured diffraction from these scalar predictions that is of interest here.

This paper presents measurements of diffraction by a set of features on a chrome mask used in optical lithography and compares the results with scalar diffraction and more rigorous vector diffraction. In the following, the system used to make the diffraction measurements will be described, as well as the technique employed to overcome vibration and alignment difficulties and build a picture of diffraction by each slit for each polarization. Each measured diffraction pattern is fit to a scalar model by minimizing the squared error and the parameters used to fit these curves are compared to determine polarization effects, amplitude

scaling, and consistency of the scalar model. Two possible explanations for departures from the model at small slit widths are considered in section 4, one based on assuming a different mask bias and the other on imperfections in the mask features.

2. MEASURING DIFFRACTION PATTERNS

The system used to measure the diffraction is shown in Figure 1. A spectrometer table has been fitted with an optical bench holding a HeNe laser (633 nm), a chopper, a polarizer and a reference detector. The spectrometer supports a motorized stage that holds the mask being measured, a 10x microscope objective for focusing the laser on the mask being measured, and a photomultiplier tube (PMT) as a detector. The output from the PMT is fed to a lock-in amplifier that is interfaced to an IBM PC XT computer to record data; this computer also controls the stepper motors that move the stage and detector as well. The apparatus is contained in a light tight box and the measurement area isolated from the other optical components by a baffle.

The features measured were twelve slits in chrome 10 um long and range in nominal width from 0.5 to 3.125 um, corresponding to 0.8λ to 4.9λ at the wavelength 633 nm used to make the measurements. It was found in initial attempts to measure diffraction by locating a slit in the beam and moving the PMT through a range of angles that excessive vibration resulted from the large stepper motor used to move the PMT. This vibration caused the beam to wander in relation to the target, introducing noise and making repeatable measurements impossible. To overcome the difficulty of aligning the laser spot accurately and the influence of vibration, an alternative approach was used. The PMT was located in a fixed angular position, and the slits, which are located side by side on the mask, were moved past the focussed laser spot while the computer continuously recorded the output from the lock-in amplifier.

A typical scan shown in Figure 2 shows twelve peaks corresponding to the intensity of energy scattered by each of the slits in to the angle where the PMT is located. The value of each of the 12 peaks was extracted from the 1000 data points, and the procedure repeated for angles from 5 to 70 degrees at 5 degree intervals for each polarization. A picture of the diffraction pattern for all twelve slits was then constructed.

3. RESULTS

Examples of the composite diffraction pattern for several slit sizes are given in Figure 3 for both polarizations. The slit widths range in size from 0.8λ to 2λ. There appears to be only small differences in the shape between the two polarizations. The larger slits have a narrow central lobe followed by minimum and maximum as a function of angle. The smaller slits show power diffracted into much broader angles.

The data for each slit was fit to a scalar model of diffraction by a slit by varying the parameters A_0 and β in the formula[6]:

$$I = \left[A_0 \frac{\sin[\beta \sin(\theta)]}{\beta \sin(\theta)} \right]^2$$

where

$$\beta = \frac{1}{2} k b = \frac{\pi b}{\lambda}$$

$$A_0 = \frac{a b}{r}$$

The parameter A_0 is the amplitude of the diffracted wave at $\theta = 0$ and the parameter β determines the shape of the diffraction pattern. The constants a, b, and r are the amplitude of the incident wave, the width of the slit, and the distance from the slit to the detector respectively. The shape and amplitude dependence for the orthogonal angle are not included in this expression since it was fixed at zero for the measured data, and in the scalar formula would have been the identical for all slits because they are the same height. Examples of this formula fit to several different slits are included as the connecting curve in Figure 3 for each polarization.

The parameter A_0 is plotted versus nominal slit width in Figure 4. To compare the behavior of the two polarizations one set of values was scaled so that A_0 for the largest slit was equal for both polarizations. Scalar theory predicts A_0 to be linear with respect to slit width b. It is evident from the figure that this is nearly true; however, there does exist some departure, which is more pronounced for the E field aligned along the slit.

If we examine the parameter β we find it is possible to determine an effective slit width from this parameter by solving for b:

$$b_{eff} = \frac{\beta \lambda}{\pi}$$

This effective slit width is plotted as a function of nominal slit width in Figure 5. This suggests that the two different polarizations see slightly different slit widths, but the difference is only about 0.1 um, or one sixth of a wavelength.

A measure of the self consistency of fitting the scalar formula to the experimental data may be found by considering the value of the 'fitting' constant arrived at by dividing A_0 by b_{eff}:

$$\frac{A_0}{b_{eff}} = \frac{a}{r} = \text{constant}$$

This fitting parameter is plotted as a function of nominal slit width in Figure 6. It is seen to be relatively constant for larger slit sizes, but as sizes on the order of a wavelength are approached it drops off abruptly. To investigate this inconsistency we turn to an electomagnetic formulation of diffraction by small slits, and consideration of total diffracted power.

4. TOTAL DIFFRACTED POWER

Using the parameters A_0 and β it is possible to calculate the total diffracted power by integrating with respect to θ from $-90°$ to $+90°$. This quantity is plotted in Figure 7 as a ratio of the measured total power to that expected from geometric optics, which would be proportional to the area. The results for each polarization are shown, with the ratio set equal to one for the largest slit size The solid line in the figure represents the same ratio found by solving the appropriate boundary conditions for the vector wave equation in elliptical coordinates[4], for the E field aligned along a slit in a thin perfect conductor. A considerable discrepancy is apparent.

A major portion of this discrepancy appears to be associated with what is assumed to be the linewidth, which is in turn a function of the quality of the mask. An SEM inspection of the mask indicated that while the top edge of the chrome agreed with the linewidth used, a small residue exists near the edge which might be optically opaque or cause scattering into the third dimension, Figure 8. If we hypothesize that the bias in making the mask was not as great as assumed, and hence the slits are smaller than their nominal width, then the measured diffracted power for the smaller slits will increase relative to the larger slits, moving the lower portion of the experimental curve up, Figure 9. The lowest solid line corresponds to the assumption of 0.125 um bias per edge, as has been assumed up to this point; reducing this bias by 0.025 um intervals until zero bias is reached results in the family of curves shown. It should be noted, however, that adjusting the bias in this manner is inconsistent with the measured value of b_{eff} as shown in Figure 5.

Examination of the mask by SEM revealed a roughness in the edges of the slits, as shown in Figure 8 for the smallest slit. This suggests that possibly a fixed amount of energy is scattered out of the plane of measurement by imperfections in the edges of the slits; this would make the smaller slits less efficient than the larger ones. To test this hypothesis we assume a fixed amount of power is scattered out of the plane of measurement, and add this back into the measured power for each slit. In Figure 10 this amount ranges from zero to 100% of the measured power of the smallest slit, added in 20% increments. At 100% reasonable agreement is achieved and this hypothesis is at least consistent with the measured value of b_{eff}.

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5. CONCLUSION

The measurement of diffraction by sub-wavelength sized features has been demonstrated by scanning the features past the laser spot and measuring the power scattered at a particular angle, and repeating for additional angles to build a total picture of diffraction. This overcomes difficulties with aligning the laser to features and maintaining alignment, as well as noise due to vibration that results from measuring one feature at a time with a moving detector. This technique has been applied to a series of twelve slits for each polarization, and is believed to show accurately feature size effects on the amount and distribution of diffracted power.

Scalar diffraction theory provides a reasonable fit to the experimental data. In comparing the parameters fit to the data it appears that wave amplitude is nearly linear with respect to slit width, and only slight polarization effects are observed. Total transmitted power appears to drop off faster than predicteded by scalar theory and is credited to the mask structure, specifically edge roughness, scattering light out of the plane of measurement. The results are consistent with rigorous electromagnetic theory but slits significantly smaller than a wavelength were not available.

The adequate performance of small slits down to a wavelength in size is a good indicator that 1x projection printing will be possible down to 0.25 um at 248 nm.

6. ACKNOWLEDGEMENTS

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[1] *SAMPLE User Guide*, Electronics Research Laboratory, Dept. of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA

[2] R. V. Jones and J. C. S. Richards, *Proc. R. Soc. London Ser. A*, **225,** 22 (1954)

[3] P. Kuttner, *Applied Optics*, **15,** 1199, 1976

[4] P. M. Morse and P. J. Rubenstien, *Physical Review*, **54,** 895 (1938)

[5] J. W. Miles, *Journal of Applied Physics*, **20,** 760, 1949

[6] F. A. Jenkins and H. E. White, *Fundamentals of Optics*, McGraw Hill Book Co., Inc. 1957

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APPENDIX I.

Measuring System and Technique

Optics and Mechanics

The system used to make the measurements consists of a spectrometer table fit with an optical bench holding a HeNe laser, chopper, beam splitter with reference diode, and polarizer. The beam was delivered to a 10x microscope objective mounted on the central stage so as to reduce vibration of laser spot with respect to the mask targets. The stage was equipped with a stepper motor to scan the mask past the laser spot. The PMT was located on a revolving arm, whose position was controled by another stepper motor. The entire apparatus was enclosed within a light tight box, and a baffle installed to separate the laser and chopper from the measurement area to minimize optical noise.

Electronics

A lock-in amplifier was used to measure the output of the PMT, with the chopping frequency supplied by the reference diode, Figure 1. The lock-in amplifier was interfaced to the PC by means of an RS-232 connection. The stepper motor positioning the PMT was under the direct control of the PC, and the stepper motor controling the lateral position of the stage was controled by a Newport stepper motor controler.

Technique

A combination of manual and automatic operation was used to make measurements. The software used in making actual measurements was relatively simple: the PC interrogated the lock-in amplifier to determine the current scale, and then continually recorded the output. One thousand values were recorded, and then stored on floppy disk with a user supplied file name. These values were later examined to find the maximums corresponding to the passage of each slit in front of the laser beam.

Several methods of measuring diffraction were tried using a fixed target and a moving detector, but it was impossible to reliably locate a target that is less than a micron across and maintain it in the beam while introducing vibration due to the movement of the PMT. An alternative approach, relying on the data handling capabilities of the PC, proved much more successful. The procedure for measuring the diffraction of all the slits in a set was to measure the light diffracted into a particular angle by each of the slits, and repeat for additional angles. Then the data for each slit is correlated to produce the desired diffraction pattern. In actual practice, care must be taken to align the mask to the laser beam so as each target 'sees' the same

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beam as it is scanned. To determine that the mask was aligned properly an optical microscope was mounted so as to project the image of the mask on the wall of the enclosure. The mask was adjusted so that the beam, approximately 8 um in diameter, was centered on each of the slits as it passed across it. This required a combination of manual angular and vertical positioning, iterated until sufficient was obtained when the stepper motor scanned across the entire set of slits. The mask was also adjusted so that the plane of the chrome on the mask intersected the waist of the focused laser beam, and the mask adjusted so that the angle of incidence was normal.

To produce a scan, the laser spot was located approximately 100 um to one side of the first slit to be measured. The PMT was adjusted to give a maximum signal; this corresponded to power coming directly through the chrome at zero degrees. Ten values of this were recorded; these values were later averaged and used to normalize the subsequent data to account for the slow drift in the laser power and the differences in the laser output for each normalization.

The mask was then moved so that the laser spot was 25 um to one side of the first slit to be measured. The PMT was carefully moved to the desired angular position to be measured; in the measurements presented here readings were made from 5 to 70 degrees in 5 degree increments. The program to record the output from the lock-in amplifier was then started, while at the same time the stepper motor on the stage was made to slowly scan the mask past the laser spot at the speed of 0.7 um/second. As each slit slides past the spot the output reaches a maximum and then declines again. The implicit assumption is that the maximum corresponds to the spot being centered on the laser beam. One may speculate that if a null occured at the angle of measurement that the peak would then be missing or breakup in to two peaks; in fact this happened only once for the nearly three hundred data peaks examined, in this case the value used was determined by using the value located in the same position for peaks in similar, better defined scans.

The movement of the stage is 'free running', it is not controlled by the computer. The reason for this is that there was not a second RS-232 port on the PC available to control the stepper motor controler. In addition, it is not possible to give one command to the stepper motor controler for it to move a full 300 um at the speed of 0.7 um/s; instead a series of commands must be issued to it to move 50 um at a time, otherwise the controler defaults to a higher speed with undesirable results. If the computer were to give these intermediate motion commands it would have to interupt it's measurements to do so, with unsatisfactory discontinuities on the scan being recorded. This limitation could be overcome in the future by programming the required commands in the stepper motor controler and installing the necessary hardware in the PC to provide the second RS-232 port.

The value of peaks on the resulting scan can be determined by direct examination of the scan files. A short program has been written that automatically locates peaks (local maxima) but it is not robust and the results were interpreted with caution. The value of these peaks for each slit were then collected to produce a pattern.

Start Up Sequence

1. Turn on laser (key switch on Hughes box). Allow to warm up for several hours to allow output to stabilize.
2. Turn on chopper - toggle switch on body of chopper.
3. Turn high voltage power supply to stand by.
4. Turn on computer monitor and computer with DOS disk in drive.
5. Turn on Newport 855C programmable controller. Consult manual for operation details.
6. Check milliampere meter; this indicates output from reference diode amplifier, check that output is around 4 mA. Adjust potentiometer (amplifier gain) or position of beam splitter in reference diode housing if necessary.
7. Using plastic glove place mask on stage and secure in place using metal clips, chrome side towards detector.
8. Manually rotate detector so that it is across the spectrometer table, out of the way so that horizontal microscope can be placed on table close to mask. Suggested lenses on microscope: 20x objective, 5x eyepiece.
9. Use manual adjustment (vertical) and stepper motor (horizontal) to locate target in beam.
10. Minimize spot size at chrome surface by focussing image of mask on enclosure wall and adjusting position of mask along beam by combination of manual positioner at bottom of stage and focussing lens positioner.
11. Locate a horizontal line and scan across using motor. If laser spot 'walks' off line, rotate mask about beam axis by using knob on top of stage and adjust vertical position. Iterate until alignment is achieved.
12. Carefully locate target features, using horizontal positioning motor, and note locations. Change Newport Motor Controller coordinate system reference for convenience if needed.
13. Remove microscope. System is now prepared for making measurements.

APPENDIX II.

IBM PC Software

NOTE: The code has been continuously modified and the versions listed here are not claimed to be complete or robust, only representative of the type of routines used to collect and analyse data for the system and technique presented in this report.

"Scanner" : BASIC program to record data from a single scan.

```
5 REM
10 REM INITIALIZATION
11 REM
15 KEY OFF:Q=1:DIM V(10):K1(1)=1:K1(2)=1:K1(3)=1:K1(4)=1
16 OPEN "COM1:1200,O,7,1,CS,DS,CD" AS #2
17 DIM MEAS(2500):DIM REF(2500)
18 PRINT "SCANNER: DO YOU WISH TO INITIALIZE LOCKIN?"
19 A$=INKEY$:IF A$="" THEN GOTO 19
22 IF A$ = "y" OR A$ = "Y" THEN GOSUB 3700
30 CLS:INPUT "Scale on lockin amplifier = ";SCALE
31 GOSUB 3754
2999 REM
3000 REM Start of data taking Routine
3001 REM
3050 SCREEN 2,0,0
3055 CLS:PRINT :PRINT
3065 INPUT "NUMBER OF DATA POINTS =  ";FINISH%
3070 CLS
3090 FOR I= 19 TO 199 STEP 30:DRAW"BM0,=I;R5"
3095 DRAW"BM157,=I;R5;BM317,=I;R5;BM477,=I;R5;BM634,=I;R5"
3100 NEXT I
3105 DRAW"BM0,19;R639;BM0,199;R639"
3110 DRAW"BM0,19;D180;BM159,19;D180;BM319,19;D180;BM479,19;D180;BM639,19;D180"
3120 CNT=0
3130 FOR N=1 TO FINISH%
3135 GOSUB 3485                        :REM TAKE A MEASUREMENT
3145 MEAS(2*N)=N                        :REM RECORD POSITION
3146 MEAS(2*N+1)=READING                 :REM RECORD DETECTOR VOLTAGE
3164 PSET (639*N/FINISH%,200-200*READING/SCALE)  :REM PLOT DETECTOR VOLTAGE
3210 NEXT N
3218 A$=INKEY$:IF A$="" THEN GOTO 3218
3219 REM
3220 REM data storage routine
3221 REM
3225 PRINT "Store Data?"
3230 A$=INKEY$:IF A$="" THEN GOTO 3230
3235 IF A$="Y" OR A$="y" THEN GOTO 3251
3240 A$=INKEY$:IF A$="" THEN GOTO 3240
3245 IF A$="Y" OR A$="y" THEN GOTO 3251
3250 GOTO 30
3251 CLS:INPUT "New File Series ";A$:IF A$="N" OR A$="n" THEN GOTO 3260
3252 IF A$ ="Y" OR A$ = "y" THEN GOTO 3255
3253 GOTO 3251
3255 CLS:INPUT "File Name   ";F$
```

--

```
3256 FILE.NO=64
3260 FILE.NO=FILE.NO+1:FILE.N$=F$+".00"+CHR$(FILE.NO)
3265 PRINT"Insert Data Disk, Press Any Key When Ready"
3270 A$=INKEY$:IF A$="" THEN GOTO 3270
3275 PRINT "Storing Data"
3276 OPEN FILE.N$ FOR OUTPUT AS #1
3277 PRINT#1,"1"
3281 PRINT#1,USING"####";FINISH%
3282 FOR I=1 TO FINISH%
3283 PRINT#1,USING"####.    ";MEAS(2*I);
3284 PRINT#1,USING"##.###^^^^";MEAS(2*I+1)  :REM STORE PMT VOLTAGE
3285 PRINT MEAS(2*I),'  ',MEAS(2*I+1)
3288 NEXT I
3309 PRINT#1,:PRINT
3315 CLOSE #1
3320 GOTO 30
3485 REM
3490 REM  Take reading from Lockin. Appropriate range should have
3491 REM  already been selected BEFORE starting program.
3496 REM
3503 PARAM$="Q1" :GOSUB 3540              :REM REQUEST DETECTOR MEASUREMENT
3504 VALUE=ABS(VAL(BUFF2$))               :REM GET MEASUREMENT
3505 READING = ABS((VALUE/2000)*(10^-INT(SENS1/3))*SENS2):REM CONVERT TO V
3529 RETURN
3530 REM ********************************************************************
3535 REM
3540 REM SUBROUTINE FOR RS232 I/O (SEND AND ECHO BACK). For reference,
3545 REM please read IBM/PC BASIC manual and Newport 855C linear actu
3550 REM ator controller's manual.
3555 REM
3560 LOCATE 1,1:PRINT"          "
3565 LOCATE 3,1:PRINT"          "
3570 LOCATE 1,1
3575 BUFFER$ ="":SIGNAL = 0
3580 PRINT PARAM$
3585 PARAM$= PARAM$+CHR$(13)
3590 FOR COUNTER = 1 TO LEN(PARAM$)
3595 VAR$ = MID$(PARAM$,COUNTER,1): PRINT #2,VAR$;
3600 IF LOC(2) <1 GOTO 3600
3605 VAR1$=INPUT$(1,#2)
3610 IF VAR$=CHR$(13) THEN GOTO 3625
3615 BUFFER$ = BUFFER$ + VAR1$
3620 NEXT COUNTER
3625 BUFF2$=""
3630 IF LOC(2) <1 THEN GOTO 3630
3635 VAR1$=INPUT$(1,#2)
3640 IF VAR1$=CHR$(13) THEN GOTO 3630
3645 IF VAR1$=CHR$(42) THEN RETURN
3650 BUFF2$ = BUFF2$ + VAR1$
3655 GOTO 3630
3700 REM
3705 REM  Activate Auto Set function in Lockin Amp,
3710 REM  wait for completion
3715 REM
3720 PARAM$="A2 1":GOSUB 3540
3725 REM PRINT BUFF2$
3730 FOR IT=1 TO 7000:NEXT IT
3732 PARAM$="ST ":GOSUB 3540
3735 REM PRINT BUFF2$
3740 STATUS%=VAL(BUFF2$) AND 32
3745 IF STATUS% = 0 THEN GOTO 3730
3750 PARAM$="A2 0":GOSUB 3540
3752 RETURN
3753 REM
3754 REM Get sensitivity setting
```

--

```
3755 REM
3756 PARAM$="S":GOSUB 3540
3760 SENS1=VAL(BUFF2$)
3765 SENS2=SENS1-(INT(SENS1/3)*3)+1
3770 IF SENS2 = 1 THEN SENS2 = 5
3775 IF SENS2 = 3 THEN SENS2 = 1
3780 RETURN
```

"SINXX.PAS": Turbo Pascal program for fitting diffraction patterns to [A*sin(c*sin(theta))/(c*sin(theta))]^2.

```
Program Sinxxfit;

{ This program fits a [A*sin(x)/x]^2 function  to a set of data          }
{ Parameters being fit are:  A and c where x = c*sin(theta)                }
{ assumption: (c -c0) = c                                             }
{                                                               }

type   datapt = array [1..2] of real;     { location & value of single data }
       dataset = array [1..14] of datapt; { a collection of data values     }

var    i,j,k: integer;                    { loop counters                 }
       A,c: real;                         { parameters being fit          }
       Points: integer;                   { number of data                }
       rawdata: dataset;                  { entire set of data            }
       sse: real;                         { sum of squared error          }
       filename:string[20];               { user supplied file name       }
       sample:datapt;                     { a data pair                   }
       maxval,minval:datapt;              { max and min of data pairs     }
       temp1,temp2,temp3,error:real;      { temporary variables           }
       minx,maxx,maxy,xscale,yscale:real; { limits and scale for plotting }
       delA,delc:real;                    { increments by which to chng A,c }
       home,home2:real;                   { values of squared error       }
       norm:real;                         { normaliz. for step to min. err. }
       step:array[1..2] of real;          { step towards min. err.        }
       fittedcurve:text;                  { curve fit to data             }
       fittedparameters:text;             { parameters fit to data        }
       angle:real;                        { units conversion              }
       RDataFile:text;                    { raw data file                 }

{$I c:lysisGRAPH.P}

function sqerr(var rawdata:dataset;       { calculate sum of squared dif-  }
           var points:integer;            { ference between data and       }
           A,c:real):real;                { function                       }
     var i:integer;
     var samp:datapt;
        ss:real;
     temp:real;
     err:real;

     begin;
       err :=0.0;
       for i := 1 to points do
       begin;
         samp := rawdata[i];
         temp := sin(samp[1]*pi/180);
         temp := samp[2]-
              sqr(A*sin(c*temp)/(c*temp));
         err := err + temp*temp;
         end;
       sqerr := err;
       end;
```

--

```
procedure plotdat(var rawdata:dataset;                 { plot data on screen   }
                var points:integer;
                var A,maxx,minx,yscale:real);
         var maxy,xscale:real;
             sample:datapt;
             i:integer;

begin;
  GraphWindow(0,0,500,99);
  ClearScreen;
  HiResColor(White);
  sample := rawdata[1];
  minx := sample[1];
  sample := rawdata[points];
  maxx := sample[1];
  xscale := 500/(maxx-minx);
  maxy := sqr(A);
  yscale := 99/maxy;

  for i := 1 to points do
  begin;
    sample := rawdata[i];
    Plot(round((sample[1]-minx)*xscale),99-round(sample[2]*yscale),1);
    end;
  end;

procedure plotAsinxx(var A,c,maxx,minx,yscale:real);  { plot function       }
         var temp1,temp2,temp3,ss:real;                 { on screen          }
             i:integer;

begin;
  for i := 1 to 50 do
  begin;
    temp1 := (i*10/500)*(maxx-minx)+minx;
    graphwindow(0,0,500,99);
    if sin(temp1)<>0 then
    begin
      temp2 := sqr(A*sin(c*sin(temp1*pi/180))/(c*sin(temp1*pi/180)));
      plot(i*10,99-round(temp2*yscale),1);
      end;
    end;
  end;

procedure printparam(A,c:real);                       { print parameters on     }
                                                { screen                  }
begin;
  window(1,18,38,24);
  gotoxy(1,1);
  writeln;
  writeln('A*sin(c*sin(theta))/(c*sin(theta)) Parameters:');
  writeln('  A  =  ',A);
  writeln('  c  =  ',c);
  end;

procedure printdel(delA,delc,k:real);            { print parameter increments }
                                                { on screen                  }
begin;
  window(42,18,80,24);
  gotoxy(1,1);
  writeln;
  writeln('Increments of parameters:');
  writeln(' delA  = ',delA);
  writeln(' delc = ',delc);
  writeln(' k     = ',k);
  end;
```

```
begin;

hires;
hirescolor(15);
gotoxy(1,15);

writeln('Enter file name : ');              {Get file name and read in data}
readln(FileName);
writeln('file name is : ',filename);
assign(RDataFile,filename);
reset(RDataFile);
for i:= 1 to 14 do
begin
  read(RDataFile,sample[1],sample[2]);
  rawdata[i]:=sample;
  end;
close(RDataFile);
Points:=14;

maxval := rawdata[1];       { locate maximum and use as initial A, find      }
minval := rawdata[1];       { initial value for c                            }
for i := 1 to points do
begin;
  sample := rawdata[i];
  if sample[2] > maxval[2] then
  begin;
    maxval := sample;
    end;
  if sample[2] < minval[2] then
  begin;
    minval := sample;
    end;
end;
A := sqrt(maxval[2]);

sample:=rawdata[points];
c:=sample[1];
sample:=rawdata[1];
c:=4*(c-sample[1])*pi/180;

printparam(A,c);            { print initial parameters                       }

plotdat(rawdata,points,A,maxx,minx,yscale); { plot data, then plot function }
plotAsinxx(A,c,maxx,minx,yscale);

delA := A/4;                       { initialize increments              }
delc  := c/4;
k:=0;
printdel(delA,delc,k);             { print initial increments           }

while k < 12 do              { twelve iterations of reducing increments }
begin;
  home := sqerr(rawdata,points,A,c);
  step[1] := sqerr(rawdata,points,A+delA/10,c)-home;
  step[2] := sqerr(rawdata,points,A,c+delc/10)-home;
  norm := sqrt(step[1]*step[1]+step[2]*step[2]);
  step[1]:=step[1]/norm; step[2]:=step[2]/norm;
  home2 :=  sqerr(rawdata,points,A-step[1]*delA,c-step[2]*delc);
  if home2 < home then
  begin;
    A:=A-step[1]*delA; c:=c-step[2]*delc;     { move towards smaller       }
    printparam(A,c);                          { squared error or...        }
    end
  else begin;
    delA:=delA/3;                             { ...reduce increments       }
```

```
    delc:=delc/3;
    k := k+1;
    printparam(A,c);writeln(' k = ',k);
    printdel(delA,delc,k);
    plotdat(rawdata,points,A,maxx,minx,yscale);
    plotAsinxx(A,c,maxx,minx,yscale);
    end;
  end;

assign(fittedcurve,'fc'+filename);          { store fitted curve,        }
assign(fittedparameters,'fp'+filename);     { fitted parameters          }
rewrite(fittedcurve);
rewrite(fittedparameters);

for i:= 1 to 70 do
begin
  angle:=i*pi/180;
  if sin(angle)<>0 then
  begin
    write(fittedcurve,i:3,' ');
    writeln(fittedcurve,sqr(A*sin(c*sin(angle))/(c*sin(angle))):8:6);
    end;
  end;
close(fittedcurve);

writeln(fittedparameters,'A = ',A:8:6);
writeln(fittedparameters,'c = ',c:8:6);
close(fittedparameters);

end.
```

Figure 1. Diffraction measuring system.

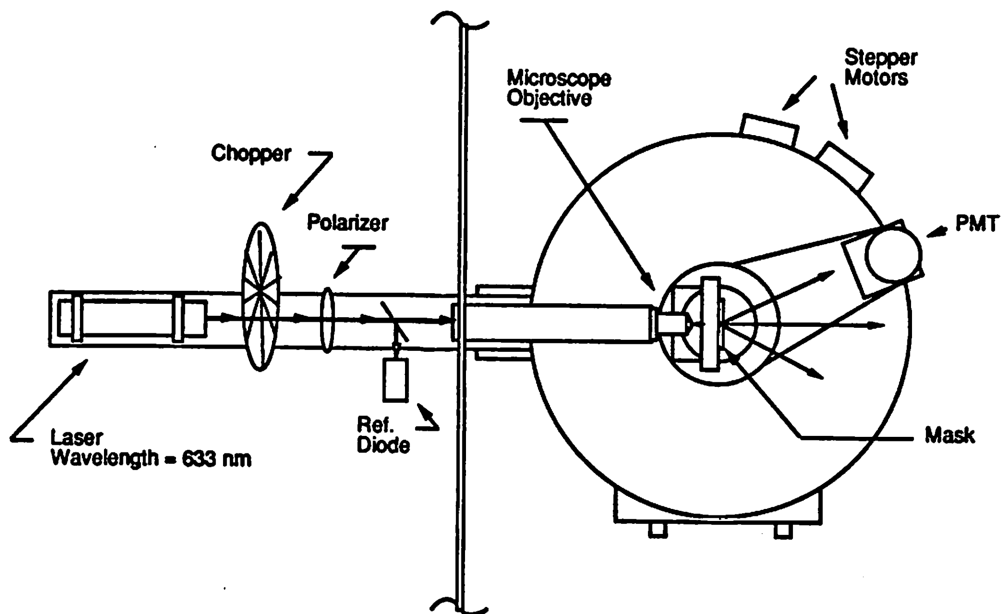

Figure 2. Typical scan: 25 degrees, E field across slit

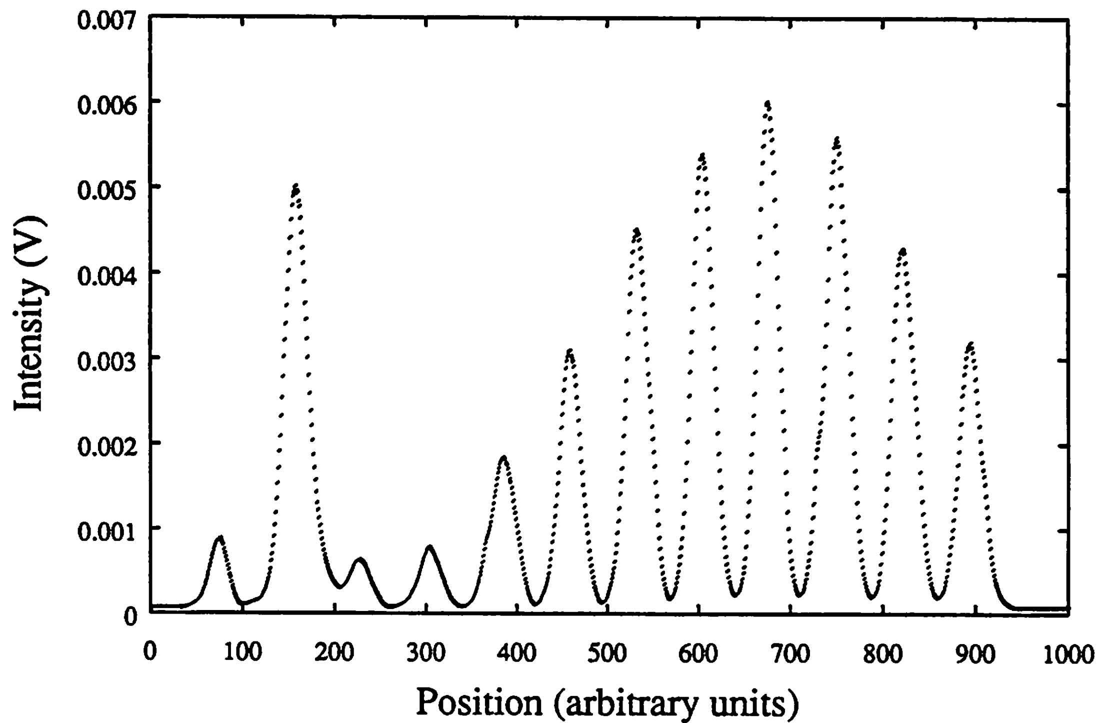

Figure 3a. Diffraction patterns: E field across slit.

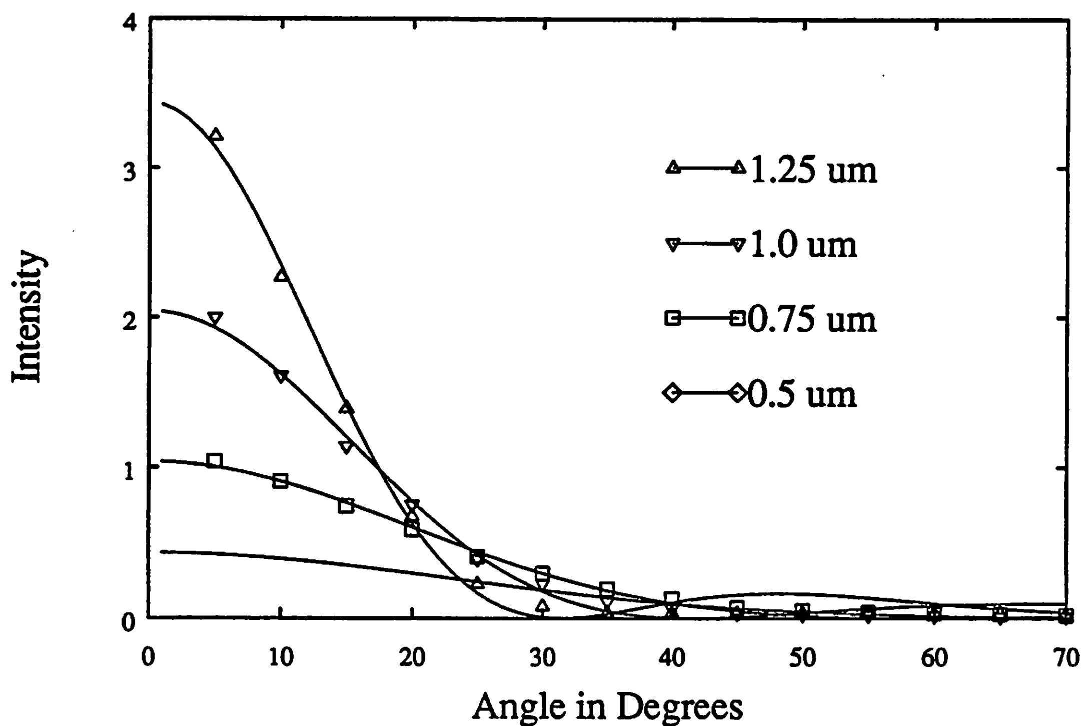

Figure 3b. E field along slit.

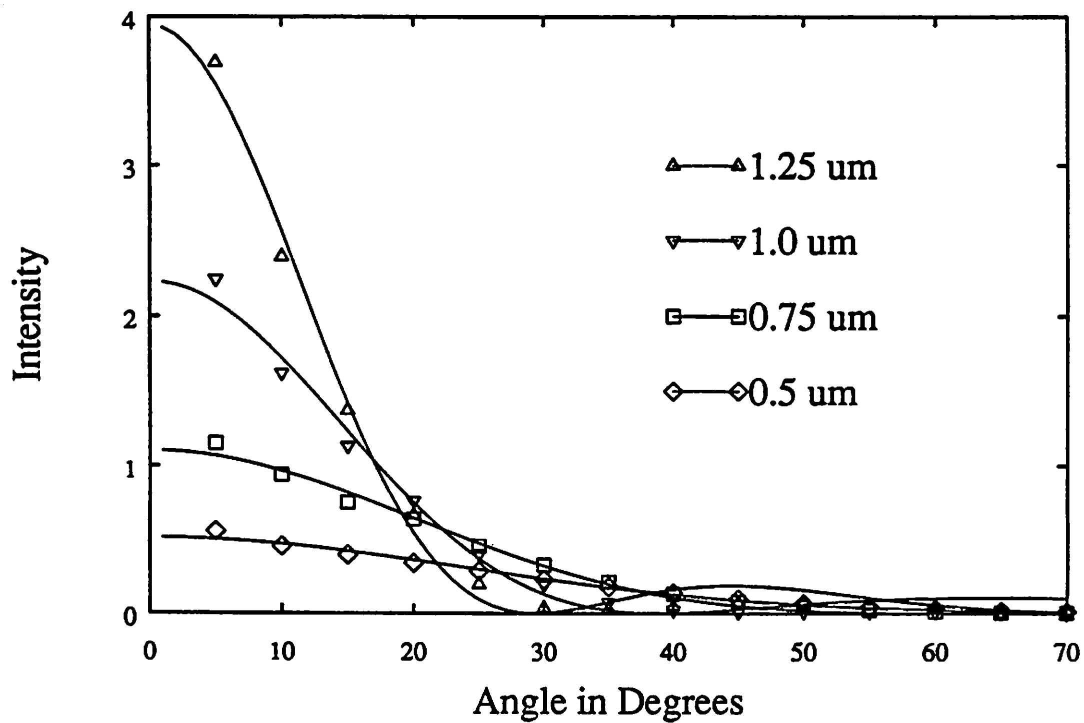

Figure 4. Parameter A_o versus slit width

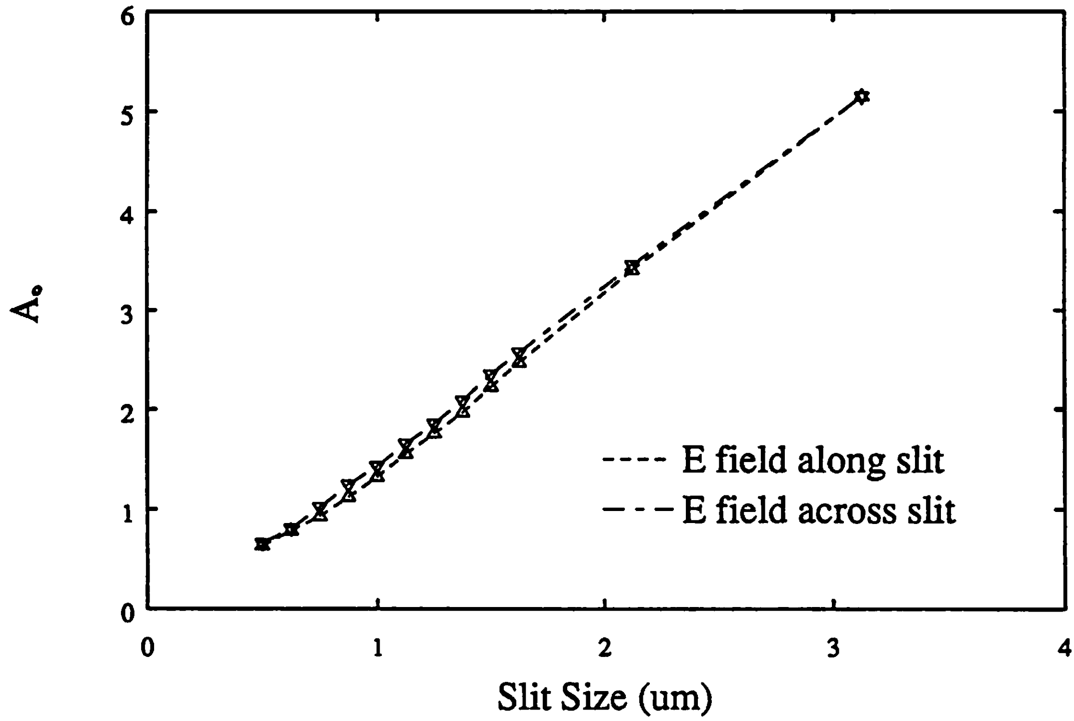

Figure 5. Effective slit size from fitted parameters.

4
3
2
1
0
Effective Size b_{eff} (um)
0
1
2
3
4
Slit Size (um)
E field along slit
E field across slit

Figure 6. Ratio of A_o over b_{eff}.

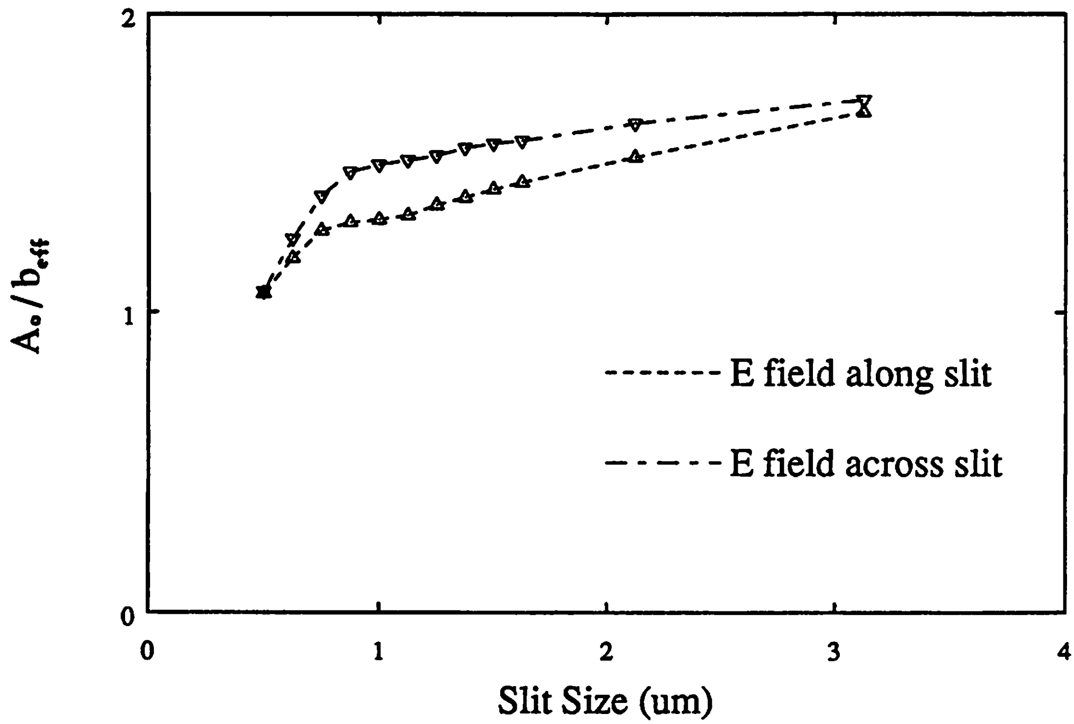

Figure 7. Ratio of measured power to geometric power.

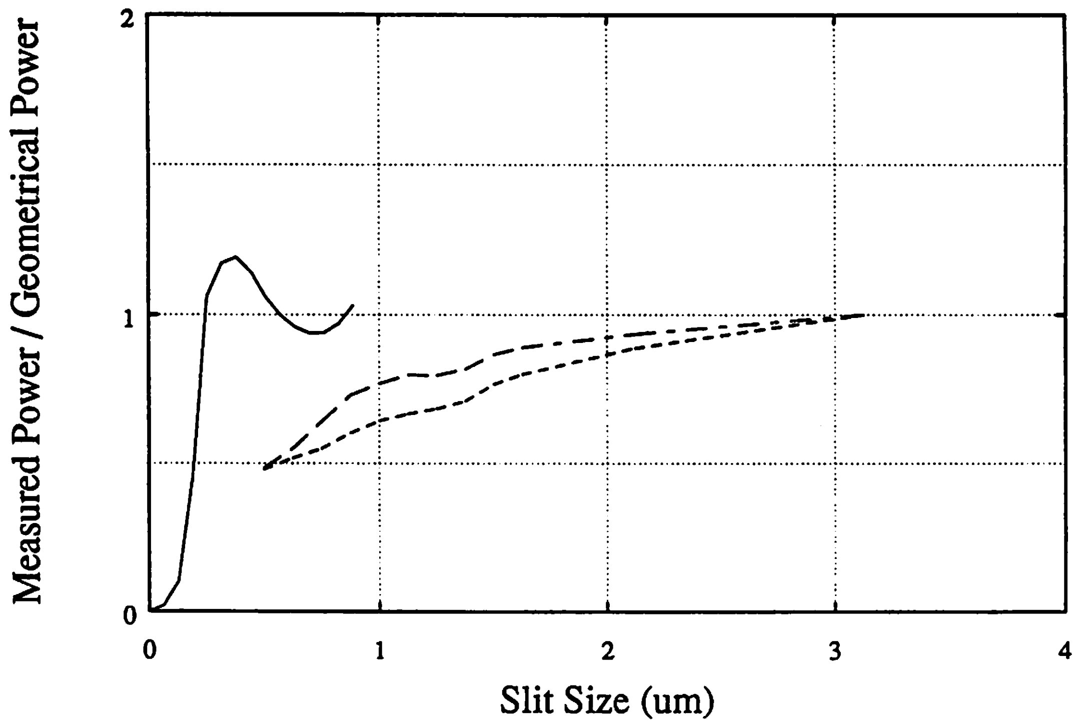

Figure 8. 0.5 um mask slit.

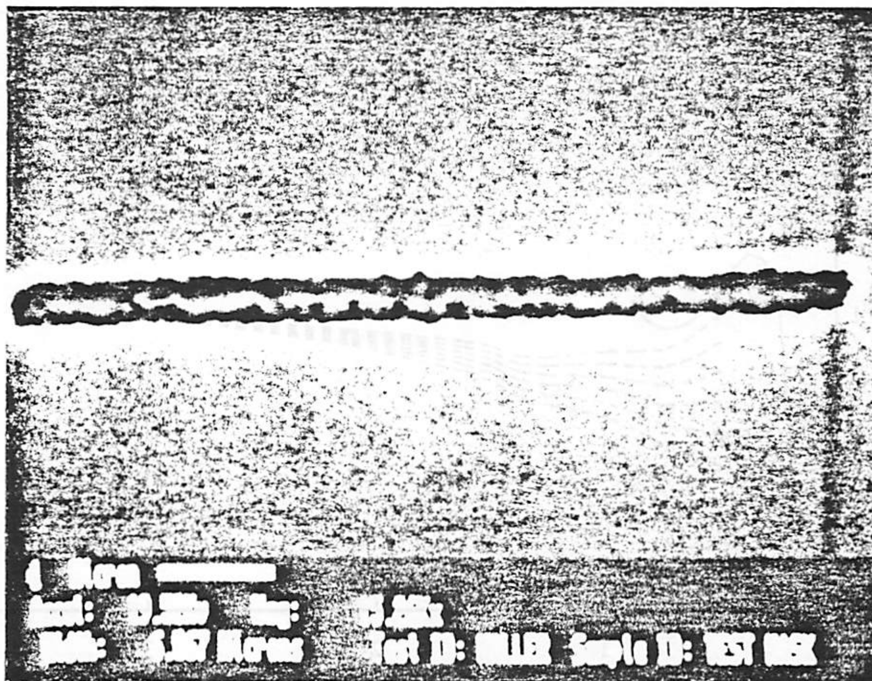

Figure 9. Varying mask bias.

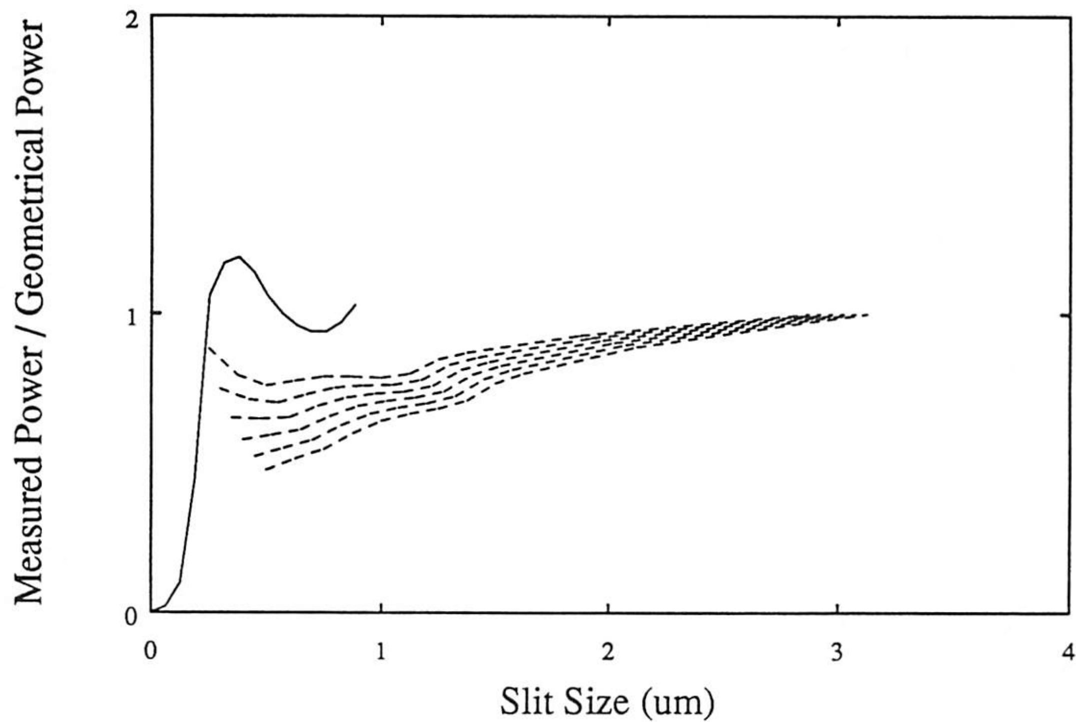

Figure 10. Adding in scattered power.