ANALYSIS OF MULTIMODE FIBER COUPLERS, TAPERS AND MODE CONVERTERS

EMTEC Engineering Inc.

C. Yeh

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APPROVED:  
LEONARD J. EYGES  
Project Engineer

APPROVED:  
ANDREW C. YANG, Chief  
Electro Optical Device Technology  
Solid State Sciences Division

APPROVED:  
ROBERT M. BARRETT, Director  
Solid State Sciences Division

FOR THE COMMANDER:  
JOHN P. HUSS  
Acting Chief, Plans Office

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THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DDC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.
This is a final report on the analysis of multimode fiber couplers, tapers and mode converters. A method based on the fast Fourier transform technique of scalar wave equation has been successfully developed to yield numerical results on a number of practical multimode fiber components. Included in this report are listings of the computer programs.
EVALUATION

This contract has provided computer simulation of the behavior of various components of fiber optic transmission systems, relevant to TPO 3B, Optical Communications. The results obtained will be useful in optimizing the design of such systems.

LEONARD J. EYGES
Project Engineer
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I. Introduction

This final report summarizes the work performed under Contract No. F19628-78-C-0206 which the Electronic Systems Division of the Air Force Systems Command granted to the EMtec Engineering, Inc. Los Angeles, California. The work was begun in August, 1978 and completed in August, 1979.

The major objectives of this R & D study were to perform theoretical and numerical analysis of multimode fiber optic components. Specifically, the following multimode components were studied: (a) Dual Fiber Couplers, (b) Fiber Tapers, (c) Fiber Horns and Branching Waveguides, and (d) Mode Converters. In the following we shall first present some background information on this subject and then our mathematical approach will be delineated. In Section III selected results of our study are then summarized. Finally, the concluding remarks and recommendations for future work will be given in Section IV. Listings of the important computer programs that we developed are also included in the Appendix.

II. Background and The Mathematical Approach

There are currently strong trends in system design toward microminiaturization digital processing and system level integration in order to achieve smaller size, weight, and power consumption, along with lower cost and improved reliability. These trends naturally point to data bus multiplexing, i.e., the interconnection of a number of spatially distributed terminals via fiber optic waveguides cables. The key component for any fiber data bus system is the fiber coupler. Since multimode singlestrand fiber is used as
a communication link in a data bus system, multimode fiber couplers
must be designed and used.

To design any coupler properly for a multimode single fiber
data bus system, detailed analysis of waveguide propagation must
be carried out. Existing techniques based on the finite elements
method,\(^1\) the coupled mode theory,\(^2\) or the geometrical optics method\(^3\)
are usually inadequate. (Detailed discussions have been included in
a review paper which would appear shortly\(^4\).) Although the finite
elements method is a very powerful approach when dealing with single-
mode fibers or couplers, it is very inefficient and costly (in terms
of computer time) to obtain any results for multimode structures.
Similarly, coupled mode theory has been used quite successfully in
predicting the coupling efficiencies of single-mode structures, but
cannot be used for multimode structures. Although the geometrical
optics method using the ray-tracing technique may yield zero-order
results for multimode structures, it is too crude to predict the
wave behavior of light signals in couplers. Recently, Arnard\(^5\)
developed a technique based on the Cook adiabatic coupler principle\(^6\)
to treat the multimode coupler problem. He claims that "it may be
used to couple two optical fibers because the dimensions are not
critical; only slowness is required". Our technique, given below,
will provide more accurate results because it does not involve making
a priori assumptions on the relevance of the dimensions of the
structure and the slowness of the coupling. Furthermore, this
technique may be used to study mode conversion effects due to the
nonuniform distribution of dielectric material within the guided
structure.

It is noted that analysis based on the scalar wave approxima-
tion has been very successful in predicting the properties of many optical devices whose characteristic dimensions are on the order of many wavelengths. The scalar wave approach is therefore preferred. We have developed an efficient numerical technique based on the scalar wave equations to solve problems dealing with multimode couplers.

It is well known that solving the exact electromagnetic equations for a spatially inhomogeneous medium is a formidable problem. Multimode couplers and mode converters can be approximated by structures with a spatially nonuniform dielectric medium. Fortunately, there are some approximations that can be made to simplify this task. First, the light wavelengths of interest are much shorter than the inhomogeneity scale length. This enables us to neglect polarization effects. Hence, the optical field can be derived from a scalar $u(x,z)$ that satisfied the reduced wave equation:

$$[\nabla^2 + k^2 n^2(x,z)] u(x,z) = 0,$$

(1)

where $k$ is the wavenumber $2\pi/\lambda$, $\lambda$ is the laser wavelength, and $n(x,z)$ is the spatially inhomogeneous refractive index of the medium. Second, if we write $u$ as the product of a factor $e^{i k n_0 z}$ that accounts for the rapid change in the phase of $u$ along the direction of propagation and a complex amplitude $A(x,z)$, a further simplification of the calculational problem results:

$$\left[ i 2 k n_0 \frac{\partial}{\partial z} + \nabla_T^2 + k^2 \left( n^2(x,z) - n_0^2 \right) \right] A(x,z) = -\frac{\partial^2 A(x,z)}{\partial x^2},$$

(2)

where $\nabla_T^2$ is the transverse Laplacian $\partial^2/\partial x^2 + \partial^2/\partial y^2$ and $n_0$ is a
given constant which represents the refractive index of some uniform medium. At laser wavelengths, the complex amplitude \( A(x) \) varies much more rapidly transverse to the direction of propagation than it does along the direction of propagation. This enables us to make the paraxial approximation and neglect the term on the right side of Eq. (2) (in the Russian literature this is called the parabolic approximation). So, the complex amplitude now satisfies

\[
\left[ i2kn_o \frac{\partial}{\partial z} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + k^2 \left( n^2(x, z) - n_o^2 \right) \right] A(x, z) = 0. \tag{3}
\]

In addition to Eq. (3), the complex amplitude satisfies an initial condition on the fiber end; at \( z = 0 \),

\[
A(x, 0) = u(x, 0) \tag{4}
\]

and the boundary condition is

\[
A(x, \pm \infty, z) = 0. \tag{5}
\]

If a truncated guassian beam is focused on one end of the optical guide, then

\[
u(x, y, 0) = u_0 \exp(-r^2/w^2) \quad \text{for} \quad 0 \leq r \leq b
\]

\[
= 0 \quad \text{for} \quad r > b,
\]

where \( r^2 = x^2 + y^2 \), \( w \) is the spot size of the beam, and \( b \) is the radius of the truncated beam at \( z = 0 \).

We have solved Eq. (3) numerically in the following manner.

Let us write \( A(x, z) \) in the form

\[
A(x, z) = \exp\left[ \Gamma(x, z) \right] v(x, z), \tag{7}
\]

where \( \Gamma(x, z) \) is a phase function associated with the medium inhomoge-
\[ \Gamma(x, z) = \frac{ik}{2n_0} \int_{z_0}^{z} \left[ n^2(x, y, z') - n_0^2 \right] dz' . \]  

(8)

The modified complex amplitude \( v(x, z) \) then satisfies the equation

\[ i2kn_0 \frac{\partial}{\partial z} v(x, z) + e^{-\Gamma} \nabla_T^2 \left[ e^{\Gamma} v(x, z) \right] = 0 . \]  

(9)

Although Eq. (9) does not look any easier to solve than Eq. (3), it is easier to solve numerically because, for sufficiently small increments in the z direction and an appropriately chosen lower limit in the integral in Eq. (8), the value of \( v(x, y, z + \Delta z) \) can be obtained to a good approximation by solving the simpler equation

\[ \left[ i2kn_0 \frac{\partial}{\partial z} + \nabla_T^2 \right] v(x, z) = 0 \]  

(10)

with the initial condition

\[ v(x, y, 0) = u(x, y, 0) . \]  

(11)

Physically, these equations approximate the propagation in the inhomogeneous medium by a two-step process at each z increment. First, we propagate the field \( u(x, z) \) at \( z \) to \( z + \Delta z \) assuming that the intervening space is homogeneous. The effect of the inhomogeneities between \( z \) and \( z + \Delta z \) is then accounted for by multiplying this solution by the phase factor \( e^{\Gamma} \).

In this research we have solved Eq. (10) by the fast Fourier transform technique. Replacing the Laplacian by its finite difference equivalent but still retaining the z derivative, the solution of Eq. (10) can be expressed in the form

\[ v(m, n, z) = \sum_{m', n'}^{N-1} v(m', n', z) \exp \left[ \frac{i2\pi}{N} (mm' + nn') \right] . \]  

(12)
where \( x = m \Delta x \), \( y = n \Delta x \), and \( V(m', n', z) \) satisfy

\[
\left[ i2 \pi n_0 \frac{\partial}{\partial z} + f(m', n') \right] V(m', n', z) = 0 \tag{13}
\]

with the initial conditions

\[
V(m', n', z_i) = \frac{1}{N} \sum_{m,n=0}^{N-1} v(m,n,z_i) \exp[i \Gamma(m,n,z_i)] \exp[- \frac{i2\pi}{N} (m'm + n'n)] \tag{14}
\]

The function \( f(m', n') \) is determined by the difference approximation used to represent the Laplacian in Eq. (10). For example, if \( V^{2}v \) is approximated by the simple central difference expression

\[
\nabla^2_T \nu = \frac{1}{(\Delta x)^2} [v(m + 1, n, z) - 2v(m, n, z) + v(m - 1, n, z) + v(m, n + 1, z) - 2v(m, n, z) + v(m, n - 1, z)] \tag{15}
\]

then \( f(m', n') \) is

\[
f(m', n') = -4 \left[ \sin^2 \left( \frac{m'n'}{N} \right) + \sin^2 \left( \frac{nn'}{N} \right) \right] \tag{16}
\]

Note that the series in Eq. (12) is simply the discrete Fourier transform of the function \( V(m', n', z) \), and thus can be evaluated numerically for a given \( V(m', n', z) \) by a fast Fourier transform algorithm. Furthermore, the function \( V(m', n', z) \) is readily determined from Eq. (13) as

\[
V(m', n', z) = V(m', n', z_i) \exp[- \frac{i2\pi}{2k(\Delta x)^2} n_0 (z-z_i)] \tag{17}
\]
where $V(m',n',z_1)$ is given by the series in Eq. (14), which can also be evaluated by a fast Fourier transform algorithm. To summarize, we will step from $z$ to $z + \Delta z$ as follows: (1) take the inverse discrete Fourier transform of $u(m,n,z) = \exp \Gamma(m,n,z) \cdot v(m,n,z)$ by means of an inverse fast Fourier transform algorithm; (2) multiply the result by $\exp \left[ -if(m',n')\Delta z/2k(\Delta x)^2n_o \right]$ and take the discrete Fourier transform with a fast Fourier transform algorithm; and (3) multiply the result by $\exp[\Gamma(m,n,z + \Delta z)]$ to yield $u(m,n,z + \Delta z)$. This process is repeated until we have reached the desired $z$ plane.

Using this algorithm we have been successful in obtaining many meaningful results for various multimode structures. These results are summarized in the following section.

III Multimode Fiber Components

Before we proceed with the presentation of the numerical results, it should be recalled that we are dealing completely with total field quantities and not with the modes. In other words, we are interested in how the total field evolves as it propagates down the guiding structure; we are not interested in how each mode propagates. Nevertheless, it is recognized that the total field may be decomposed into a set of orthonormal guided modes. For example, an incident Gaussian beam with a given beamwidth $w$ may excite many modes in a parabolic-index-profile fiber when $\alpha > 1$ or when $\alpha < 1$ with

$$\alpha = (2\lambda a)/[nn_a w^2(2\delta)^{1/2}]$$

or may excite only one mode when $\alpha = 1$. Only the $\alpha = 1$ single mode will propagate down the parabolic-index-profile guide without experiencing the focusing and defocusing effects. For $\alpha \neq 1$ cases, the
input Gaussian beam will experience focusing and defocusing effects. Another way to interpret the above phenomenon is that multimodes with different propagation constants are excited by the input beam when $\alpha \neq 1$, while only single mode is excited when $\alpha = 1$. The stronger are the focusing-defocusing effects, the higher is the content of different modes.

(a) Dual Fiber Couplers

The geometry of a multimode inhomogeneous fiber coupler is shown in Fig. 1. Two graded-index fibers with index variation given by

$$n(r_{1,2}) = n_a \left(1 - \frac{r_{1,2}^2}{a_{1,2}^2}\right),$$

where $r_{1,2}$ are the radial coordinates of 1 and 2 fibers, respectively, and $n_a$, $\delta$, $a$ are all known constants, are fused together as shown. The separation distance between the centers of the fibers is $d$. A Gaussian beam representable by

$$u(x,y) = u_0 \exp\left\{\left[-\left(x + \frac{d}{2}\right)^2 - y^2\right]/w^2\right\},$$

where $u(x,y)$ is the scalar wave function of the beam, and $u_0$, $w$ are given constants, is incident on one of the fibers. We wish to learn how this beam evolves as it propagates down the coupled structure. In other words, the coupling distance and the beam shape will be obtained.

Results of our investigation on the multimode dual fiber couplers are shown in Figs. 2-5. It is seen that if two identical parabolic-index fibers were placed side by side with each other
Fig. 1. The fiber coupler.
FIBER COUPLER

\( d_x = 5\mu \)
\( \alpha = 0.42 \)
SEPARATION \((-\frac{1}{4}, \frac{1}{4}) = 40\mu \)

EACH STEP = 3902\mu

a. 50\mu, 50\mu, 10\mu
b. 50\mu, 30\mu, 10\mu
c. 50\mu, 30\mu, 10\mu

Figure 2
and if the beamwidth were so chosen that \( \alpha = 1 \) is obtained, one would expect the guided power to interchange between the two fibers in a periodic manner with a distinct single coupling length. On the other hand, if \( \alpha \) departs from unity, many modes are generated and many beat coupling lengths occur, so the guided power will no longer interchange among the guides in a simple manner. For the \( \alpha << 1 \) or \( \alpha >> 1 \) case, even larger numbers of modes are excited. Depending upon how the incident energy is distributed among the excited modes the back and forth (periodic) power exchange phenomenon could still prevail if the major amount of incident energy is distributed in several low-order modes. Only when the incident energy is distributed evenly among all modes and only in the limit of infinite number of modes will the input power be split in a 50-50 manner between the two fibers.

Sample program listing and printout for the evolution of field intensities in the two unequal fiber coupler are given in Appendix A.

(b) Fiber Tapers

Fiber tapers have been commonly used to inter-connect two optical waveguides of different cross-sectional sizes or shapes. The effects of the transition on the guided fields are shown in Figs. 6-10. It can be seen that very profound effects on the guided fields are found. Extensive mode conversion may be present even for gently varying tapers. Sample printout for the evolution of field intensities in the presence of the fiber tapers is given in Appendix B.

(c) Fiber Horns and Branching Waveguides.

Numerical computations to obtain the field behavior in a
TAPER EFFECTS OF TAPER RATES
$\alpha = 0.42$
$R_0 = 50 \mu$
$F_R = 50 \mu$, $50 - 10 \mu$ DIFFERENT SLOPES
STEP SIZE $= 487 \mu$

NO TAPER
TAPER $50 \mu$, 10 STEPS
TAPER $50 \mu$, 20 STEPS

Figure 6
multimode fiber horn structure or in a branching fiber guide have also been carried out using the similar technique outlined earlier. The cross-sectional index profiles are specified for each step in the direction of wave propagation. Shown in Figs. 10-11 are plots of beam waist as a function of the longitudinal distance for various different incident beam sizes.

(d) Mode Converters.

There exist many occasions when the presence of high order modes rather than low order modes is preferred in a multimode fiber. It is known that nonuniform distribution of dielectric materials with different indices of refraction within a fiber may cause mode conversion. Taking advantage of this phenomenon, one may design a low-order-modes to high-order-modes converter using nonuniformly distributed dielectrics. For example, one such converter may be the following structure:

The cross-sectional index profile may have the following form:
It is anticipated that the low order modes will be affected more by the discontinuities. Thus energy in the low order modes may be converted into that of the high order modes as expected. Other means of generating high order modes using variations of the above scheme may also be envisioned.

To evaluate the efficiency of this type of mode converter, and to learn the intensity distribution of the resultant field, the evolution of an incident beam through this channel should be obtained. We have successfully developed a program which is capable of providing such information. Illustrative example is given in Appendix C. It can be seen that ring-shaped higher order modes can easily be generated by the introduction of a slight dip in the index profile as proposed above.

IV. Conclusions and Recommendations for Future Work

We have successfully developed a computational technique, based on the scalar wave - FFT method, to treat problems dealing with various multimode fiber components, such as, fiber couplers, fiber tapers or horns, fiber branches or mode converters. The only significant restriction to keep in mind is that index variations of the structure under consideration must be gentle. This consideration is normally satisfied in most practical situations. The basic objective of this R & D study is, thereby accomplished. Listing of the computer program is given in the Appendix. By simply specifying the index profile at each longitudinal z-step and knowing the initial beam shape, one may generate the propagation characteristics of the beam as it propagates down the structure.

Using this program, we were able to trace the evolution of
a given beam as it propagates down a given multimode graded index fiber structure. If the multimode structure were a multimode coupler made with two or more paralleled graded index fibers in close proximity of each other, we can predict the coupling distances as well as the power distribution of the beam in such coupler; if the structure were a tapered or a flared multimode fiber, we were able to learn whether a given tapered structure or a given horn structure could still confine or guide a given beam; if the structure were a mode converter made with multimode fiber containing an on-axis dip in its index profile, we can learn the effectiveness of such a dip in converting lower order modes to higher order modes.

To achieve such capabilities, an extensive amount of computer software was developed.

In the course of these studies, a number of important new research topics were generated. For example, it is known that the FFT scalar wave approach requires that the index profile be gently varying. But the quantitative definition of "gently" must still be specified. (We wish to push our ability to deal with almost step-index profile fibers.) Initial indication (through our computer results) seem to show that even with rather steep index gradient, adequately accurate results were still obtainable. This problem also leads to the need for us to study the possible usage of adaptive coordinates to improve the beam resolution as it propagates down the multimode structure. Another problem which is directly related to the case of induced beam radiation caused by variations in the guiding structure is also of great interest. Perhaps the
introduction of a lossy surface for the outer boundary of our computer mesh may provide a means of estimating the radiation loss. Associated with beam radiation problem in the case of beam reflection caused by variations in the guiding structure, the reflection coefficient may be obtained by correctly summing over incremental reflection coefficients (i.e., taking into account the phases of the reflected waves) which occur whenever wave energy propagates from a region with a certain index value to another region with a different index value.

With the help of our newly developed program, the principal thrust of the future work should be to study realistic multimode fiber structures, such as data-bus type multi-channel couplers, tapered or flared transition joints, multimode fibers with non-ideal parabolic index profiles and to obtain data for these realistic situations.
Personnel:

The principal contributors of this contract have been:

C. Yeh  
Senior Research Engineer

K. Casey  
Senior Research Engineer

F. Manshadi  
Research Engineer

S. Chang  
Research Engineer
REFERENCES

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Appendix A

Fiber Coupler
PROGRAM OPTF13(INPUT,OUTPUT,FILE0,TAPES=INPUT,TAPC=OUTPUT,
* TAPE7=FILE0)
C******************************************************************************
C INPUT PARAMETERS
C**********************************************************************
C CARD 1 (15 FORMATS)
C 1 CASES NUMBER OF CASES TO BE READ
C CARD 2 (NAMELIST FORMAT=DEFAULT)
C LAMDA WAVE LENGTH (MICRONS)
C RU 1/E POINT IN IRRADIANCE (MICRONS)
C FR FIBER RADIUS (MICRONS)
C N REFRACTIVE INDEX
C PCORP PERCENT ORUP AT HFR OF N/NU
C QURAD OUTER RADIUS (MICRONS)
C DX MESH SPACING (MICRONS)
C NSTEPS NUMBER OF Z-STEMS
C NDZINC LENGTH OF Z-STEM = ZMIN/NDZINC
C IOUT DEVICES NUMBER FOR OUTPUT
C PGKEY DEVICE NUMBER FOR GREYSCALE OUTPUT
C PGKEY IF TRUE PRINT IRRADIANCE PROFILE AT EACH STEP
C PLAIST IF TRUE WRITE 2ND MOMENTS AT EACH STEP
C PLTMAX IF TRUE PLOT PEAK INTENSITY VS DISTANCE
C PLTFLD IF TRUE PLOT FIELD AT END OF PROPAGATION ALONG I
C MESH GRID SIZE (32, 64, OR 128)
C******************************************************************************
C COMMON /LCM2/REFNDX(16384),Sn(128),CS(128),ZTS(128),PLSU(128)
C + ,AMPARY(16384),RADARY(16384)
CLEVEL 2,REFNDX,SN,CS,ZTS,PQS,AMPARY,RADARY
C DIMENSION WSK(256),MU(2)
C DIMENSION MU(3),Y(3),PCORP(3),FRA(3),REFCFA(3)
C COMMON /ARRAYS/V(2666)
C COMMON /PARAM/OZINC,MESH,LAMDA,RO,FR,RO,PCORP,OUTRAD,OX,NSTEPS,
C + NDZINC,MESHSZ,SZSZ,PI,RAVENH,DX1,MS,NS,OF,IN,NSHPS
C REAL LAMDA, RO, NOSQ, N2
C LOGICAL PGKEY, PLAIST, PLTMAX, PLTFLD, LAST, CALLPX
C DATA P73.141592657,ICNTCS/7,ICNT/707
C NAMELIST /DEFAULT/LAMDA,RO,FR,RO,PCORP,OUTRAD,OX,NSTEPS,NDZINC,
C + IOUT, IGREY, PGKEY, PLAIST, PLTMAX, PLTFLD, LAST, CALLPX
C READ(5,1000) NCASES
C READ(5,*) XB,YB
C READ(5,1000) NF18
C READ(5,*) (X0(I),Y0(I),I=1,NF18)
C WRITE(6,*) (X0(I),Y0(I),I=1,NF18)
C READ(5,*) (PCORPA(K),K=1,NF18)
C WRITE(6,*) (PCORPA(K),K=1,NF18)
C WRITE(6,*) (FRA(K),K=1,NF18)
C WRITE(6,*) (FRA(K),K=1,NF18)
C 1000 FORMAT(15)
C 1 READ(5,DEFAULT)
C
ICNT=0
FLAG=NO/ABS(NO)
NO=ABS(NO)
IF(FLAG.LT.1) WRITE(IOUT,2050)
2050 FORMAT(2,/47M THE REFRACTIVE INDEX IS A CONSTANT EQUAL TO NO)
PCORP=PCORPA(1)
FR=FRAT(1)
WRITE(IOUT,DEFAULT)
C
C
CALCULATE CONSTANTS
MESH=2*MESH
MESH2=MESH**2
MESH3=MESH**3
MN2NU=0.2*PCORP/FR**2
ZMIN=PI/12.*SQR(HN2NU))
DZINC=ZMIN/NDZINC
OXS=OZINC/ZMIN
OXS6=OXS/2.

DATA(2.*PI/LAMBD0)
DETH=2.*ZMIN*OXS/(MENAME*NO))*/(PI/(MESH*OZET*RO))**2
FTCNST=(1.-1./MESH)*PI
XY0=MESH/2.
RANNU=UOUTRAD/RO)**2
RN0=NU*KN0**2
NU(1)=MESH
NU(2)=MESH
AXINU=OXS1
LAST=.F.
IF(FLAG.LT.1) RFCF=0.
CALL PORE.T.RH.PMAST.RH.PLTST.RH.PLMAY.RH.PLTF0.RH.PLIFL
C
C
WRITE THE IMPORTANT CALCULATED PARAMETERS
WRITE(IOUT,2000) ZMIN,OZINC,HN2NU,ALPHA
2000 FORMAT(2,9H ZMIN = ,F10.4,IX,7HMICRONS,/,9H OZINC = ,F10.4,IX,+
+7HMICRONS,/,9H HN2NU = ,E10.3,1X,13HMICRONS**((-2),/,+
+9H ALPHA = ,F10.5,/) )
C
C
CALCULATE NECESSARY ARRAYS
DO 800 K=1,NFI
X0(K)=X0(K)+X0
Y0(K)=Y0(K)+Y0
RFRF(K)=NO**20.02*PCORP(K)**(RO/FRAT(K))**2/2.
890 CONTINUE
DO 100 K=1,MESH
RK=K-1
ANG=FTCNST*RK
CS(K)=COS(ANG)
SN(K)=SIN(ANG)
SET UP REFRACTIVE_INDEX_ARRAY

M=0
DO 120 J=1,MESH
DO 10 I=1,MESH
M=M+1
IMPNX=0.
DO 110 K=1,MFSIZE
L1=((J=1,-1)*DZET)**2
L2=((K=1,-1)*DZET)**2
RAD=L1+L2
IMPNX=IMPNX+1
IF (IMPNX,MFSIZE) GO TO 10
110 CONTINUE
REFNX(N)=IMPNX(1.)
120 CONTINUE
IF (I.EQ.52.OR.I.EQ.58) WRITE(IOUT,*) REFNX(N)
130 CONTINUE
CALL GREYSC(IGREY,10,REFNDX,MESH,MESH,MS,MF,1,NS,NF,100,0.,
+ 6*REFNDX+5)

SET UP INITIAL FIELD

N=1
K=0
CH=AVENM*ZMIN*DXSIG/(2.*NO)
DO 140 G=1,MESH
DO 10 I=1,MESH
M=M+1
10 CONTINUE
Z2=((I-XO=1)*DZET)**2
RAD=Z2+Z2
IF (RAD,GT,RAUNRM) GO TO 20
AMP=EXP(-RAD/2.)
AMP=CH*REFNDX(K)
V(K)=AMP*COS(AKG)
V(KP1)=AMP*SIN(AKG)
GO TO 140
20 CONTINUE
V(0) = 0.
V(AP) = 0.
140 CONTINUE
IF(CALLPR) CALL PRINTER(ICNT)

DO PROPAGATION
DO 500 ICNT = 1, NSTEPS

CONDITION V FOR TRANSFORM
K = 1
DO 160 J = 1, MESH
SNJ = SN(J)
CSJ = CS(J)
DO 160 I = 1, MESH
K + 1
SNI = SN(I)
CSI = CS(I)
AK = CSJ * CSI - SNJ * SNI
AL = (CSJ * SNI * CSI * SNJ)
VR = V(K)
V = V(KP1)
V(K) = VR * AR - VI * AI
VI(KP1) = VI * AI + VR * AL
160 CONTINUE

DO TRANSFORM
CALL FORT(V, MU, 2, 1, WORK)

SOLVE FIRST ORDER ODE
K = 1
DO 180 J = 1, MESH
PM1 = ETAT * PQ3(J)
DO 180 I = 1, MESH
K + 2
PM2 = ETAT * PQ3(I)
VR = V(K)
V = V(KP1)
ANG = (PM1 + PM2)
CANG = COS(ANG)
SANG = SIN(ANG)
V(K) = (VR * CANG - VI * SANG) * R/NORM
(V(KP1) = VR * SANG + VI * CANG) * R/NORM
180 CONTINUE

DO INVERSE TRANSFORM
CALL FORT(V, MU, 2, -1, 1, WORK)

RECONDITION V BECAUSE OF TRANSFORM

- 34 -
**OPTF13**

```
DO 200 J=1,MESH
SNJ=SN(J)
CSJ=CS(J)
DO 200 I=1,MESH
K=K+2
KP1=K+1
SN=SN(I)
CSI=CS(I)
AR=CSJ*CSI-SNJ*SN
AI=CSJ+SNJ*CSI
VR=V(K)
VI=V(KP1)
V(K)=VR*AR-VI*AI
V(KP1)=VR*AI+VI*AR
200 CONTINUE

NON INCLUDE EITHER FULL STEP OR HALF STEP REFRACTIVE INDEX EFFECTS DEPENDING ON WHERE IN THE PATH YOU ARE

IF(ICHNT.EQ.NSTEPS) XSIMUL=DXSIN
KE=1
CH=WAVENM*ZMIN*XSIMUL/(2.*NO)
DO 220 M=1,MESHSU
ARG=ÆENDA(M)+CH
AR=CSJ(ARG)
AI=SNJ(ARG)
KE=2
KP1=1
VR=V(K)
VI=V(KP1)
V(K)=VR*AR-VI*AI
V(KP1)=VR*AI+VI*AR
220 CONTINUE
IF(ICHNT.EQ.NSTEPS) LAST=1.
IF(CALLPR) CALL PRINTER(ICHNT)
500 CONTINUE

CALCULATE IRRADIANCE PATTERN AND PRINT

IF(PGREY) GO TO 30
ME=0
DO 240 K=1,MSHSQ2,2
VR=V(K)
VI=V(KP1)
MS=1
RADARY(M)=VR**2+VI**2
240 CONTINUE
CALL GREYSL(IGREY,10,RADARY,MESH,MESH,MS,MF,1,NS,NF,U..U..U..U.
+10IRRADIANCE,10)
30 CONTINUE
IF(NCASES.EQ.1) GO TO 1
END
```
SUBROUTINE PEAK(VMAX)
COMMUN /LCM2/REFD0A(16384),SN(120),CS(120),Z1E=120),P5SU(120)
+ AMPAR1(16384),KADARY(16384)
LEVEL 2,REFD0A,SN,CS,Z1SU,P5SU,AMPAR1,KADARY
COMMUN /PARAM/DEZINC,MESH,LAMBDA,RO,F,R0,PCURP,OUTRAD,LX,HTCS;
+ MESH2,MESH30,MESH302,PI,HAVEMM,DX1S1,5,NS,MP,IF,MINTS
L=0
SUML=0.
VMAX=0.
DO 10 K=1,MESHSu2,2
V=W(K)
KI=K+1
VI=V(KP1)
VRAD=V(K2+VH*2)
IF(K.EQ.MESHSu2) SUML=SUML+VRAD
IF(K.GT.MESHSu2) SUML=SUML+VRAD
VMAX=A.MAX(VMAX,VRAD)
KADARY(L)=VRAD
10 CONTINUE
T0=SUML+SUMR
SUML=SUML/T0
SUMR=SUMR/T0
WRITE(0,2000) SUML,SUMR
2000 FORMAT(/,1X,7HSUML=,E14.7,3X,7HSUMR=,E14.7,/) RETURN
END

REFERENCE MAP (R=1)

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SUBROUTINE GREYSC(IFILE, NLEVEL, AMAT, I1, I2, J1, J2, MIN, IMAX, IDEL, TITLE, CHAP) 

LEVEL is a DIMENSION ICHARS(10, 5), LINE(132, 5), LEVEL(10), AMAT(IDIM, JIDM) 
DIMENSION TITLE(20) 
DATA ICHARS/1H, 1H, 1H*6000000000000000, 1H++, 5*1H+ 
t/61H, 1H++, 2400000000500000000000000000, 1H++, 5*1H+ 
DATA IBOM0H/1H++, 1BLANK/1H+ 
DATA LEVEL/01, 3E2, 3/ 
DATA KCP/107, 1/ 
DATA NLMAX /59/ 
IFILEX=-IFILE 

GREYSC 

PURPOSE--PRODUCES A SHAPED (GREY-SCALE) LINE PRINTER PLLOT OF 
A TWO-DIMENSIONAL, REAL MATRIX. 

USAGE--CALL GREYSC(INFILE, NLEVEL, AMAT, I1, I2, J1, J2, MIN, IMAX, IDEL, 
JOIN, JMAX, JOEL, AMIN, AMAX, TITLE, CHAP) 

IFILEX (OUTPUT FILE CODE. + FOR LBL. = FOR OTHER SYSTEMS OR TERMINAL 
FILE) (THE NO. OF GREY-LEVELS TO BE PRINTED) 
AMAT (THE 2D MATRIX TO BE DISPLAYED) 
IDIM (THE FIRST DIMENSION OF MATRIX AMAT) 
JOIN (THE SECOND DIMENSION OF MATRIX AMAT) 
IMIN (THE BEGINNING I-COORDINATE FOR THE PLOT) 
JMIN (THE ENDING J-COORDINATE FOR THE PLOT) 
IDEL (USED IN THE SENSE ...[MIN, MAX, IEL]) 
JOEL (MAX, JOEL SEE IMIN, IMAX, AND IDEL DESCRIPTIONS) 
AMIN (THE MINIMUM VALUE USED FOR SCALING--SEE BELOW) 
AMAX (THE MAXIMUM VALUE USED FOR SCALING--SEE BELOW) 
TITLE (CHARACTER VECTOR OR MOLLERITH STRING FOR TITLE) 
CHAP (NO. OF CHARACTERS IN TITLE VECTOR) 

SUBPROGRAM REFERENCES--(NONE) 

COMMENTS-- 
1. CREATED 7/2/74 BY C. SOUT 
2. NLEVEL CAN BE NO LARGER THAN 1+9. IF =5, CHARACTERS 
   ARE NOT OVERPRINTED. IF BETWEEN 8 AND 9, CHARACTERS 
   OVERPRINTED NO MORE THAN ONCE. IF =10, THE DENSIEST CHARACTER 
   WILL BE OVERPRINTED TWICE. 
3. SCALING IS LINEAR BETWEEN AMIN AND AMAX. IF AMIN=AMAX, 
   SCALING WILL BE AUTOMATICALLY SET TO FULL RANGE FOR THE MATRIX. 
4. MACHINE COMPATIBILITY--CHANGE VARIABLE KCP IN DATA STATEMENT 
   TO INDICATE NUMBER OF CHARACTERS PER WORD FOR THE MACHINE. 
5. PLOT BORDER--DEFAULT IS A BORDER OF ASTERISKS. TO RESET THE 
   PLOT BORDER, CHANGE THE VARIABLE BORDER IN THE DATA STATEMENT. 
   (ALGORITHM WILL CORRECTLY HANDLE THE BLANK BORDER CASE). 
6. CHANGED 7/31/74 TO HANDLE CASE OF 5 CHAR/WORD. 
7. CHANGED 8/12/74 TO CHANGE SIXTH CHARACTER TO A SIMPLE \"\'. 
8. CHANGED 9/2/77 TO DEFINE CHAR. 5-7 AS (+, THE H SIGN), (+ PLUS X). 
9. CHANGED 9/12/77 TO ALTER PAGE HANDLING. THIS ROUTINE WILL NOW 
   TRY TO FIT BOTH THE SCALING INFORMATION AND THE GREYSCALE PLOT 
   ON THE SAME PAGE, WITH SCALING INFORMATION BELOW THE PLOT. 
   NLMAX REPRESENTS THE MAXIMUM ROWS FOR THE INPUT MATRIX STIL
ALLOTTING THE SCALING INFORMATION TO APPEAR ON THE SAME PAGE.

SCALE, IF NECESSARY

\[ \text{AMAX} = \text{AMAX} \]

\[ \text{IFILE} = \text{AMAX} \text{(FILEX)} \]

\[ \text{AMIN} = \text{AMIN} \]

\[ \text{AMAX} = \text{CT, AMIN} \text{GO TO 100} \]

\[ \text{AMAX} = 1.0,0 \]

\[ \text{DU 50} \text{ I=JMIN, IMAX, IDEL} \]

\[ \text{DU 50} \text{ J=JMIN, JMAX, JDEL} \]

\[ \text{AMAX} = \text{AMAX} \text{(AMN, AMAT(I, J))} \]

\[ \text{SU 100} \text{ CONTINUE} \]

PRINT HEADER

\[ \text{NWORDS} = (\text{NCHAN}-1)/\text{NCPA}+1 \]

\[ \text{IF (NCPA=E0.6) WRITE ([FILE, 1040]) (TITLE(I), I=1, NMAXORDS) } \]

\[ \text{IF (NCPA=G0.4) WRITE ([FILE, 1041]) (TITLE(I), I=1, NMAXORDS) } \]

\[ \text{IF (NCPA=E0.10) WRITE ([FILE, 1042]) (TITLE(I), I=1, NMAXORDS) } \]

\[ \text{IF (AMAX.EQ.AMN). RETURN} \]

PREPARE A LINE FOR PRINTING

\[ \text{LINE(1,1)=IBORDR} \]

\[ \text{JLOC} = (\text{JMAX-JMIN})/\text{JDEL}+3 \]

\[ \text{LINE(JLOC+2,1)=IBORDR} \]

\[ \text{LINE(1,2)=IBLANK} \]

\[ \text{LINE(1,3)=IBLANK} \]

\[ \text{LINE(JLOC+2,2)=IBLANK} \]

\[ \text{LINE(JLOC+2,3)=IBLANK} \]

\[ \text{LASTL=LASTL-I} \]

\[ \text{WRITE ([FILE, 1045]) (IBORDR, I=1, LASTL1)} \]

\[ \text{DU 400} \text{ I=JMIN, JMAX, IDEL} \]

\[ \text{DU 250} \text{ J=JMIN, JMAX, JDEL} \]

\[ \text{250} \text{ CONTINUE} \]

\[ \text{LINE(J,II)=IBLANK} \]

\[ \text{LEY}=1 \]

\[ \text{J=2} \]

\[ \text{U 300} \text{ JJ=JMIN, JMAX, JDEL} \]

\[ \text{J=J+1} \]

\[ \text{L=(AMAT(I, JJ)-AMN)/(AMX-AMN)*FLOAT(NLEVEL)+1} \]

\[ \text{L=MAXO(1, L)} \]

\[ \text{L=MINO(NLEVEL, L)} \]

\[ \text{LEY=MAXO(LEV, LEVEL(L))} \]

\[ \text{LEV=LEVEL(L)} \]

\[ \text{DU 300} \text{ K=1, LEVNO} \]

\[ \text{LINE(J, K)=ICHAMS(L, K)} \]

\[ \text{300} \text{ CONTINUE} \]

FIND LAST PRINT POSITION
CONTINUE

IF(IFILE.NE.0.AND.KL.EQ.LEV) WRITE(IFILE,1050) (LINE(II,KL),
   1 II=1,KK)
IF(IFILE.EQ.0.AND.KL.EQ.LEV) WRITE(IFILE,1060) (LINE(II,KL),
   1 II=1,KK)

CONTINUE

WRITE(LAST_LINE(BORDER))
WRITE(IFILE,1070) (IGORDR,I=1,LASTLI)

PRINT TRAILING SCALE INFORMATION

DO 200 I=1,NLEVEL
   AMIN=FLOAT(I-1)/FLOAT(NLEVEL)*(AMX-AMMN)+AMN
   XMAX=XMIN+DELTA
   DO 175 J=1,LEV
      IF(IFILE.EQ.0.AND.J.EQ.LEV) WRITE(IFILE,1020) ICARS(1,J),XMIN,
         1,MAXX
      IF(IFILE.LT.0.AND.J.EQ.1) WRITE(IFILE,1020) ICARS(1,J),XMIN,
         1,XMAX
   CONTINUE
   175
200 CONTINUE

1000 FORMAT(1HO,20A0)
1001 FORMAT(1HO,20A4)
1002 FORMAT(1HO,12A10)
1003 FORMAT(1HO,24A5)
1010 FORMAT(1HO,52HKEY-SCALE CHARACTERS AND RANGES/1X)
1020 FORMAT(5X,4A5,5X,4S,E15.6,5X,E15.6)
1030 FORMAT(1M*, 4X,A1)
1034 FORMAT(1M1)
1040 FORMAT(1M1/4X,20A6)
1041 FORMAT(1M1/4X,20A4)
1042 FORMAT(1M1/4X,12A10)
1043 FORMAT(1M1/4X,24A5)
1045 FORMAT(1HO,132A1)
1050 FORMAT(1X,132A1)
1060 FORMAT(1M*, _132A1)
SUBROUTINE SIZE (ARRAY, MESH, MESHN, X0, Y0, X2, Y2)

THIS ROUTINE DETERMINES THE LOCATION OF THE CENTROID AND THE HAVING SQUARE WIDTH OF AN ARRAY

PARAMETERS

ARRAY REAL DIMENSIONAL INPUT ARRAY
MESH ARRAY HAS DIMENSION MESHX MESHN
X0, Y0 X, Y COORDINATES OF CENTROID
X2, Y2 X AND Y RNS WIDTHS OF ARRAY

LEVEL 2, ARRAY
DIMENSION ARRAY (MESH, MESHN)
M0=MESH/2+1
M1=MESH/2+1
SUM1=0.
SUM2=0.
SUM3=0.
SUM4=0.
SUM5=0.
DO 10 M=1, MESHN
KM=M-M0
KM=KM+1
DO 10 M=1, MESHN
KM=M-M0
KM=KM+1
KM2=KM*KM
SUM3=SUM3+KM2
SUM4=SUM4+RM*KM
SUM5=SUM5+KM
10 CONTINUE
SUM1=1./SUM5
X0=SUM1*SUM2
Y0=SUM1*SUM1
X2=3.*Y0+SUM4-X0*X0
Y2=SUM3+Y0*Y0
X2=SUM1*(X2)
Y2=SUM1(Y2)
RETURN
END

REFERENCE MAP (R=1)
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.213 CP SECONDS
LAMBDAT = 0.8E+00,
KU = 0.5E+02,
FK = 0.5E+02,
NU = 0.15E+01,
PCDNP = 0.81E-03,
OUTRAD = 0.1E+04,
DX = 0.5E+01,
NSTEPS = 40,
NOZINC = 5,
IOUT = 6,
IGREY = 6,
PCREY = 1,
PAAIST = 1,
PLTINST = F,
PLTMAX = F,
PLTFLE = F,
MESH = 128,
SEND

ZMIN = 19513.3742 MICRONS
DZINC = 3902.0748 MICRONS
M2NU = 0.645E-08 MICRONS**(-2)
ALPHA = 0.42179
**IMRADIANCE**

**GREY-SCALE CHARACTERS AND RANGES**

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**IMRADIANCE**
INHABITANCE

GREY-SCALE CHARACTERS AND RANGES

\[
\begin{array}{cc}
0.3375\times 10^{-7} & 0.33453 \times 10^{0} \\
0.33453 \times 10^{0} & 0.33453 \times 10^{0} \\
0.33453 \times 10^{0} & 0.33453 \times 10^{0} \\
\vdots & \vdots \\
0.33453 \times 10^{0} & 0.33453 \times 10^{0} \\
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\]

\[0.2575 \times 10^{1}\]
**Irradiance**

**Grey-Scale Characters and Ranges**

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IRradiance

GREY-SCALE CHARACTERS AND RANGES

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<td>130825Ec+01</td>
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INRADIANCE

GREY-SCALE CHARACTERS AND RANGES

<table>
<thead>
<tr>
<th>Character</th>
<th>Decimal Value</th>
<th>Gray Scale Range</th>
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<tbody>
<tr>
<td>z</td>
<td>1.7528e-01</td>
<td>1.7428e+01, 1.7505e+01</td>
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<tr>
<td>0</td>
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<td>3.4505e+00, 3.4607e+00</td>
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<td>5</td>
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<td>x</td>
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</table>
INRADIANCE

GREY-SCALE CHARACTERS AND RANGES

- .545799E-07 - .220249E+00
- .262244E+00 - .452547E+00
- .452547E+00 - .670841E+00
- .670841E+00 - .905146E+00
- .905146E+00 - 1.18147E+01
- 1.18147E+01 - 1.53777E+01
- 1.53777E+01 - 57 - 1.94055E+01
- 1.94055E+01 - 1.81035E+01
Appendix B

Fiber Taper
<table>
<thead>
<tr>
<th>LOAD RM</th>
<th>OPTFDB</th>
<th>CYBER LOADER 1.3-452</th>
<th>04/01/74</th>
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<tbody>
<tr>
<td>USL. RM</td>
<td>150200</td>
<td>71 SL-SYS10</td>
<td>11/08/77</td>
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<tr>
<td>CHE. RM</td>
<td>130217</td>
<td>257 SL-SYS10</td>
<td>11/08/77</td>
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<tr>
<td>WLS. RM</td>
<td>150220</td>
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<td>FLD. RM</td>
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<td>CDP. RM</td>
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<tr>
<td>CELV. RM</td>
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<td>11/08/77</td>
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<td>LKL. RM</td>
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<td>11/08/77</td>
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<td>KEK. RM</td>
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<td>11/08/77</td>
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<tr>
<td>FSL. RM</td>
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<td>11/08/77</td>
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<td>FLEG. RM</td>
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<tr>
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207 CP SECONDS  150200H CM STORAGE USED  97 TABLE MOVES  64
DEFAULT

LAMXDA = .6E+00,

MU = .5E+02,

FR = .5E+02,

NU = .15E+01,

PDDMP = .81E-03,

OUTRAD = .1E+04,

DX = .5E+01,

NSTEPS = 40,

NZINC = 40,

IOUT = 0,

IGREY = 0,

PUGREY = 1,

PAAIST = 1,

PLTMAX = F,

PLTMST = F,

PLTFLE = F,

MESH = 128,

SEND

ZMIN = 1951.5752 MICRONS
DZIN = 467.8344 MICRONS
NZ2ND = 0.646E+06 MICRONS**(-2)

ALPHA = .42174

50.

THIS IS STEP 0

BEAM MAIST IN X AND Y DIRECTIONS IS 49.99995 49.99995 MICRONS
**IMMADIANCE**

---

**IMMADIANCE**

**GREY-SCALE CHARACTERS AND RANGES**

<table>
<thead>
<tr>
<th>Value 1</th>
<th>Value 2</th>
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<tr>
<td>$225655e-09$</td>
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<tr>
<td>$1101359e+00$</td>
<td>$1143122e+00$</td>
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### Resistance

**Gray-scale Characters and Ranges**

<table>
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<tr>
<th>Resistance</th>
<th>Value</th>
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<tbody>
<tr>
<td>3752 x10^-4</td>
<td>0.4078 x10^0</td>
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<td>1 x10^-4</td>
<td>1.6938 x10^0</td>
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<tr>
<td>1.5933 x10^-4</td>
<td>2.0735 x10^0</td>
</tr>
<tr>
<td>2.5453 x10^-4</td>
<td>3.3571 x10^0</td>
</tr>
<tr>
<td>3.3071 x10^-4</td>
<td>4.2539 x10^0</td>
</tr>
<tr>
<td>4.0354 x10^-4</td>
<td>5.0817 x10^0</td>
</tr>
<tr>
<td>4.2007 x10^-4</td>
<td>5.2370 x10^0</td>
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</tbody>
</table>
Appendix C

Mode Converter
PROGRAM UPFIAR(INPUT, OUTPUT, FILED, TAPES=INPUT, TAPE2=OUTPUT, + TAPES2=FILED)

C******************************************************************************
C INPUT PARAMETERS
C******************************************************************************
C CARD 1 (IS FORMAT)
C CASES NUMBER OF CASES TO BE READ
C CARD 2 (NAMELIST FORMAT=DEFAULT)
LAMDA WAVE LENGTH (MICROMS)
MO ICE POINT IN IRRADIANCE (MICROMS)
FM FIBER RADIUS (MICROMS)
NU REFRACTIVE INDEX
PCRCP PERCENT DROP AT N=PR OF N
OUTRAD OUTER RADIUS (MICROMS)
DX MESH SPACING (MICROMS)
STEPS NUMBER OF Z-STEP
NLINC LENGTH OF Z-STEP = ZMAX/NDINC
IOUT DEVICE NUMBER FOR OUTPUT
IGKEY DEVICE NUMBER FOR CHEYSY OUTPUT
POREY IF TRUE PRINT IRRADIANCE PROFILE AT EACH STEP
FAIAST IF TRUE WRITE 2ND MOMENTS AT EACH STEP
PLTMAX IF TRUE PLOT 2ND MOMENTS VS DISTANCE
PLTFLD IF TRUE PLOT FIELD IRRAD AT END OF PROPAGATION ALONG I
PLTFLD IF TRUE PLOT FIELD IRRAD AT END OF PROPAGATION ALONG J
MESH GRID SIZE (32, 64, OR 128)
C******************************************************************************
C COMMON /LCM2/REFNOX(16384),SN(128),CS(128),ZT(128),PDSU(128)
+ .AMATORY(16384),RADARY(16384)
LEVEL 2:REFNOX,SN,CS,ZT,PDUS,AMATORY,RADARY
DI:ENSION NOIX(256),NOI(2)
C COMMON /ARRAYSY(32/2)
C COMMON /PARAM/NDINC,MESN,LAMDA,KD,FR,NO,PCRCP,OUTRAD,OX,NSTEPS,
+ NLINC, Lịch, MESN, PDP5, PLTMAX, DRIVER, IOUT, IKEY
+ ,PLTLD, PLTFLD
C REAL LAMDA, NO, NOSU, N2
C LOGICAL POKEY, FAIAST, PLTMAX, PLTFLD, PLTFLD, LAST, CALLPR
C DATA FR1.41543571, IGKEY1.1, IC1107
C NAMELIST /DEFAULT/LAMDA, FR, NO, PCRCP, OUTRAD, OX, NSTEPS, NLINC,
+ IOUT, IKEY, POKEY, FAIAST, PLTMAX, PLTFLD, PLTFLD, LAST, CALLPR
C READS(5,1000) NCASES
READ(5,*) USPX, USPI
READ(5,USPX, USPI)
1000 FORMAT(*)
1 READS(5, DEFAULT)
C IGKEY=0
FLAG=0/ABS(0)
CASES(0)
IF(FLAG.LT.0.) WHILE(IOUT,2050)
2050 FORMAT(//,92 THE REFRACTIVE INDEX IS A CONSTANT EQUAL TO NU)
     WHILE(IOUT,DEFAULT)
CALCULATE CONSTANTS

MESH = 2 * MESH
MESH2 = MESH ** 2
AShSw2 = 2 * AShSwS
MN2N = 0.2 * PCUmP / FH ** 2
ZL1NE = PI / (2 * SQRT(RH * NLU))
DULNc = CM1 * NLUZINC
DUL = DULC / CM1
ASh = DShZ / 1.2
UZET = 0 * X/HU
AVENM = 2 * PI / LAMDA0
E = 2 * ZMIN * DXSI / (AVENM * NU) * PI / (MESH * DZET * RU) ** 2
FLC = 1 - 1. / MESH * PI
XYU = MESH / 2
RANRNM = (NU * RAD / NLU) ** 2
RU = NU * RAD
K0 = 2 * NU ** 2 / 2
ALPHA = 2 * ZMIN / (PI * AVENM * NU * RU ** 2)
NOG = NU ** 2
MU(1) = MESH
MU(2) = MESH
ASMUL = DASI
LSTF = F.
IF (FLAG = LF(0)) REFCF = 0.
CALLP = PAGCY, OR, PLAIST, OR, PLTWS, TH, OR, PLTMAX, OR, PLTFLD, OR, PLTFL

WRITE THE IMPORTANT CALCULATED PARAMETERS

WRITE (OUT, 2000) ZMIN, DZINC, RH2NU, ALPHA

2000 FORMAT (/H, 139, ZMIN = /F10.4, 1X, 7HMCRONS, /, 9H DZINC = /F10.4, 1X,
+ 7HMCRONS, /, 9H RH2NU = /E10.3, 1X, 13HMCRONSS=-2), /,
+ 9H ALPHA = /F10.5, /)

CALCULATE NECESSARY ARRAYS

DO 100 K = 1, MESH
  KX = K - 1
  CSK = CM (SK)
  SIN (SK) = SIN (SK)
  ZIS (K) = (R*K - XYU) * UZET ** 2
  POSG (K) = (R*K - XYU + 5) ** 2
  CONTINUE

SET UP REFRACTIVE INDEX ARRAY

IF (MESH .NE. 128) GO TO 10
M = MESH / 4 + 1
MV = M * MESH / 2 - 1
NS = NS
IF = 1
10 CONTINUE
NS = 1
NS = 1
#F = MESH
NF = MESH

40 CONTINUE
CALL MINDX(DSPX, DSVY, NOSJ, DZET, AYO, HEFC, 1)

C C SET UP INITIAL FIELD

M = 1
K = 0
CS = AVENH * ZHMIN * DXSIM / (2. * NU)
DO 140 J = 1, MESH
Z1 = ZTSU(J)
DO 140 I = 1, MESH
K = K + 1
M = M + 2
NPI = M + 1
Z2 = ZTSU(I)
RAD = Z1 + Z2
IF (RAD.GT.RAD.Ref) GO TO 20
AM = EXPI(-RAD/2.*)
APG = CS * PFNDX(K)
V(m) = AM * COS(ARG)
V(nPI) = AM * SIN(ARG)
GO TO 140
CONTINUE
V(m) = 0.
V(nPI) = 0.
CONTINUE
IF (CALLPH) CALL PRINTER(Icnt)
GO PROPAGATION
GO 500 Icnt = 1, NSteps

CONDITION V FOR TRANSFORM
K = 1
DO 160 J = 1, MESH
SNJ = SN(J)
CSJ = CS(J)
DO 160 I = 1, MESH
K = K + 2
NPI = M + 1
SI = SN(I)
CSI = CS(I)
A = CSJ * CSI * SNJ * SN
AII = (CSJ + SNJ + CSI + SNJ)
V = V(KJ)
V(PI) = VM + VH = V1 * AI
V(nPI) = V1 * AN + VM * AI
CONTINUE

GO TRANSFORM
CALL FUNKT(V, MU, Z, 1, 1, WORK)
SOLVE FIRST ORDER UDE

k = 1
DE 180 J = 1, MESH
PH1 = ETAN * POSG(J)
DE 180 I = 1, MESH
k = 2
PH2 = ETAN * POSG(I)
VR = V(K)
V = VR(P1)
W = (PH1 + PH2)
CA = COS(Angle)
SA = SIN(Angle)
V(A) = (VR*CANG - V1*SANG)*RNorm
V(KP1) = (VR*SANG + V1*CANG)*RNorm
180 CONTINUE

DO INVERSE TRANSFORM

CALL FOUNT(V, MU, 2, -1, 1, WORK)

RECONSTRUCTION V BECAUSE OF TRANSFORM

k = 1
DE 200 J = 1, MESH
SJ = S(R(J))
CJ = CJ(J),
DE 200 I = 1, MESH
k = 2
PI = P1
SI = S(I)
CI = CI(I)
AI = CJ*I - SJ*SI
RI = CJ*SI - SJ*CI
VR = V(K)
V = VR(P1)
V(KP1) = VR*AI + V1*AR
200 CONTINUE

NOW INCLUDE EITHER FULL STEP OR HALF STEP REFRACTIVE
INDEX EFFECTS DEPENDING ON WHERE IN THE PATH YOU ARE

IF(ICH1.EQ., NSTEMP) * SIMUL = DXSIM
k = 1
CM = AVEH * CMIN * SIMUL/(2.*NO)
IC = INTEGER
CALL PINDEX(NPX, NPY, NO, OZ, XZ, YZ, REFCF, ICH1)
ON 200 M = 1, MESH
AH = EXFLUX(M, J, CH)
AI = COS(Angle)
AR = SIN(Angle)
k = 2
PI = P1
VR = V(K)
```
PROGRAM OPTIFIS  76/176  OPT1=2

230  V1=V(K$1)
     V(K$1)=V*K$2-V1*K$3
     V(K$1)=V*K$3+V1*K$2
     CONTINUE
     IF (ICNICS.EQ.NCASES) LNAS1=1.
     IF (CALLPR) CALL PRINTER(1CN1)

250  CONTINUE

CALCULATE INRAVANCE PATTERN AND PRINT

240  IF (PURITY) GO TO 30

245  M=0
     DO 240 K=1,MSH502,2
     M=K
     V1=V(K$1)
     M=M+1
     MAURY(M)=VR**2+VI**2
     CONTINUE
     CALL GHEYSU(IGNET,10,PMARY,MESH,MESH,NS,NF,1,NS,NF,1,0,0,0,
       +10,INRAVANCE,10)

250  CONTINUE

ICNICS=ICNICS+1
     IF (ICNICS.LE.NCASES) GO TO 1

END

SYMBOLIC REFERENCE MAP (K=1)

KEY POINTS

F14  OPTIFIS

PIAGLES  SHAPE  TYPE  RELOCATION
073   AI   REAL   7691  ALPHA   REAL  ARRAY
070   AM   REAL   41602  AMPARY  REAL  ARRAY
116   AN   REAL   7164  AN     REAL
105   ARG  REAL   7043  ARG    REAL
041   CALLPR  LOGICAL   7113  CARG  REAL
007   CH   REAL   49209  CS     REAL
105   LSY  REAL   7104  LSY    REAL
105   USX  REAL   7044  USX    REAL
10   UX   REAL   7116  UX     REAL
17    XSI  REAL   7051  XSI    REAL
052   UPE  REAL   0  UZINC  REAL
052   UZE  REAL   4  FR     REAL
045   FLAS  REAL   7072  I     INTEGER
054   FITCST  REAL   5672  ICNICS  INTEGER
073   ICT  INTEGER  6  IGNET  INTEGER
115   IGN1  INTEGER  7070  J     INTEGER
115   ICNT  INTEGER  7101  KPI   INTEGER
212   LAMBD  INTEGER  1  LAST  LOGICAL
212   K    INTEGER  7046  MESH2  INTEGER
212   KEMR  INTEGER  7073  MIP  INTEGER
212   KEPS  INTEGER
212   KF  INTEGER
```
SYMBOLIC REFERENCE MAP (K=1)

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<th>RINDEX</th>
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<table>
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<td>ARRAY</td>
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<td>ACMUT</td>
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</tr>
<tr>
<td>61</td>
<td>CONSS2</td>
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<tr>
<td>60</td>
<td>DZP</td>
<td>REAL</td>
<td>*UNUSED</td>
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<td>59</td>
<td>DZI</td>
<td>REAL</td>
<td>PARAM</td>
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<td>58</td>
<td>DZINC</td>
<td>REAL</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>I</td>
<td>INTEGER</td>
<td>PRTPL1</td>
</tr>
</tbody>
</table>
SDFALT

LAMDA = .8E+00,
RO = .125E+02,
FR = .5E+02,
NO = .15E+01,
PCURP = .33E-01,
OUTAD = .1E+04,
DX = .3E+01,
NSTEPS = 40,
NDZINC = 10,
LOUT = 6,
IMGREY = 6,
PGREY = T,
PAALST = T,
PLTST = F,
PLTMAX = F,
PLTFLO = F,
PLTFLE = F,
MESH = 128,
SEND

ZMIN = 3057.1532 MICRONS
DZINC = 305.7156 MICRONS
KM2ND = .254E-06 MICRONS**(-2)
ALPHA = 1.05730
### Inaudiance

#### Grey-Scale Characters and Ranges

<table>
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<th>Character</th>
<th>Value</th>
</tr>
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<td>2.170142e+11</td>
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<tr>
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<td>5.558282e+11</td>
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<tr>
<td>.033742e+11</td>
<td>3.374237e+10</td>
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<tr>
<td>.111000e+00</td>
<td>1.110000e+01</td>
</tr>
<tr>
<td>.015931e+00</td>
<td>1.593159e+00</td>
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<tr>
<td>95</td>
<td>1.593159e+00</td>
</tr>
</tbody>
</table>

---

*Note: The diagram includes a circular pattern with asterisks, possibly representing frequencies or values in a visual format.*
INRADIANCE

GRAY-SCALE CHARACTERS AND RANGES

-1.95306E-07  2.6749E-01
-2.498E-01     5.9143E-01
-5.6127E-01    9.147E-01
-1.1259E+00    1.1123E+01
-1.4057E+00    1.4057E+01
-1.6039E+00    1.6039E+01
-1.9532E+00    1.9532E+01
Impedance

Grey-scale characters and ranges

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<th>Value</th>
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Note: Values are approximate and subject to error.
INRADIANCE

GREY-SCALE CHARACTERS AND RANGES

\[ \begin{align*}
43,734,425 \times 10^4 & & 1,717,922 \times 10^6 \\
179,735,401 & & 55,431,052 \\
359,476,014 & & 59,421,546 \\
732,921,589 & & 71,893,544 \\
3,509,991 \times 10^5 & & 1,964,563 \times 10^6 \\
1,076,456 \times 10^5 & & 1,631,762 \times 10^6 \\
1,258,178 \times 10^6 & & 1,457,932 \times 10^6 \\
\end{align*} \]
### IMMADIANCE

#### GREY-SCALE CHARACTERS AND RANGES

<table>
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- 106

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MISSION
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