

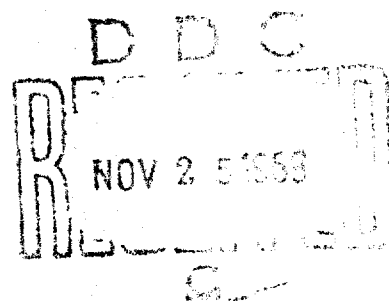
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A Computer Program to Analyze Optical Parametric Up-Conversion Processes in Nonlinear Crystals

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ABSTRACT

A Fortran computer program has been developed which analyzes a nonlinear material to determine (a) the range of IR wavelengths that can be converted in a phase matched (PM) process, (b) the PM orientation of the wave vectors for critical and non-critical PM, (c) the angular aperture for PM conversion, and (d) the maximum number of resolvable lines for image conversion. These characteristics are determined as a function of IR wavelength for a given pump wavelength, pump radiation divergence, and length of nonlinear crystal.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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A COMPUTER PROGRAM TO ANALYZE OPTICAL PARAMETRIC UP-CONVERSION PROCESSES IN NONLINEAR CRYSTALS

INTRODUCTION

Infrared (IR) light can be up-converted to visible light, via a parametric process, in crystals which have a nonlinear susceptibility (1-3). In the second-order processes considered here, IR light of frequency ω_{IR} is mixed with intense light of frequency ω_P , called the pump light. The result is signal light of frequency $\omega_S = \omega_{IR} + \omega_P$. For the process to be efficient, the crystal must be transparent at the three frequencies involved, and momentum must be conserved; i.e., the process must be "phase matched" (PM). A process is PM if the directions of propagation in the nonlinear crystal for the three frequencies of light can be found such that the signal wave vector equals the sum of the pump and IR wave vectors, i.e., $(k_P + k_{IR}) - k_S = 0$.

Given a nonlinear crystal, it is necessary to find the range of IR wavelengths that can be up-converted in the material and to find the characteristics of the up-conversion process as a function of the IR wavelength. Up-conversion of IR to the visible necessitates the use of an intense source of laser light as a pump whose wavelength is near the long-wavelength edge of the visible spectrum. Once the wavelength of the pump source has been specified, the range of ω_{IR} for PM up-conversion can be determined. Then for each set of frequencies ω_P , ω_{IR} , and ω_S , the orientation of the crystal with respect to the wave vectors that gives a PM up-conversion, i.e., the phase match angles, can be found. In each case the wave vectors can be either collinear or noncollinear, and both situations must be considered. Also, if the IR to be up-converted carries spatial information such as an image, one must determine such things as the acceptable angular aperture for PM up-conversion, the resolution limit* for the beam divergence of a given pump, and the orientation which maximizes the angular aperture. Further, all of the characteristics of a PM up-conversion process must be calculated as a function of ω_{IR} , the IR frequency.

Finding the PM angles and other characteristics of an up-conversion process means solving transcendental equations. To obtain any desired accuracy the complete analysis is best done on a computer using an iteration technique. This report describes a Fortran IV program which does that analysis. The characteristics of the nonlinear crystal necessary for the analysis are its limits of transparency and its refractive indexes as a function of wavelength.

The next section describes the mathematical basis of the calculation. This is followed by a description of the program itself and two appendixes which give a listing of the program, sample input data, and the corresponding output.

MATHEMATICAL FORMULATION

The requirements for PM up-conversion (4) are

$$\omega_P + \omega_{IR} = \omega_S \quad (1)$$

and

*The resolution limit considered here is the particular case of an extreme multimode pump source with the IR image and pump source optically at infinity with respect to the nonlinear crystal. See, for example, "IR Image Optical Parametric Up-Conversion," R.A. Andrews, IEEE J. Quant. Electr., Jan. 1970.

$$\mathbf{k}_P + \mathbf{k}_{IR} = \mathbf{k}_S \quad (2)$$

where the subscripts P , IR , and S refer to pump, infrared, and signal, respectively, and $\mathbf{k}$ is the corresponding wave vector. For a crystal of length L , PM up-conversion takes place as long as

$$\Delta k = |\Delta \mathbf{k}| = |\mathbf{k}_P + \mathbf{k}_{IR} - \mathbf{k}_S| \leq \frac{2\pi}{L} \quad (3)$$

where for convenience we assume that Δk is measured along the direction of $\mathbf{k}_S$ as shown in Fig. 1. In general, the orientation of the nonlinear crystal for PM up-conversion is given by the solution to the following equation:

$$\Delta k = \left[\frac{n^i(\omega_P, \theta_P)}{\lambda_P} + \frac{n^j(\omega_{IR}, \theta_{IR})}{\lambda_{IR}} \cos \phi \right] \sec \rho - \frac{n^k(\omega_S, \theta_S)}{\lambda_S} = 0 \quad (4)$$

where

ϕ = angle between $\mathbf{k}_P$ and $\mathbf{k}_{IR}$

ρ = angle between $\mathbf{k}_P$ and $\mathbf{k}_S$

θ_ℓ = angle between the Z -axis and $\mathbf{k}_\ell$ ($\ell = P, IR, S$)

$i, j, k = O$ or E for extraordinary or ordinary polarization

It is assumed that the parametric process is confined to the yz plane, where x , y , and z are the optical axes of the nonlinear crystal, and z is the optical axis for a uniaxial crystal. However, the crystal may be optically biaxial; therefore

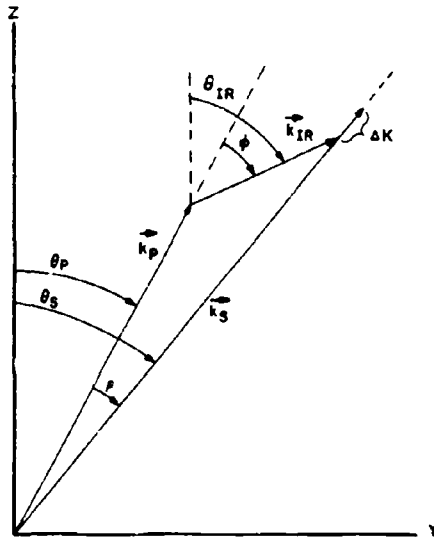


Fig. 1 - Crystal geometry for up-conversion from infrared to visible wavelengths

$$n^O(\omega, \theta) = n_x(\omega) \quad (5)$$

and

$$n^E(\omega, \theta) = \left\{ \frac{\sin^2 \theta}{[n_y(\omega)]^2} + \frac{\cos^2 \theta}{[n_z(\omega)]^2} \right\}^{-1/2}, \quad (6)$$

where n_x , n_y , and n_z are the refractive indexes for light polarized along the x , y , and z directions.

Solutions to Eq. (4) and, in particular, collinear up-conversion ($\phi = \rho = 0$) represent examples of critical phase matching. The noncritical phase matching (NCPM) solution (Ref. 7) requires that

$$[\partial \Delta k(\theta_P, \phi) / \partial \phi]_{\theta_P} = 0 \quad (7)$$

The crystal has finite length L and up-conversion will take place whenever $\Delta k < 2\pi/L$. Hence, for a fixed pump beam direction, there will be a range of values of ϕ for which IR light will be up-converted. This range defines the angular aperture α for k_{IR} and is defined by all values of ϕ such that for a fixed value of θ_P ,

$$\Delta k(\phi, \theta_P) < 2\pi/L \quad (8)$$

or

$$\alpha = |\phi_1 - \phi_2|, \quad (9)$$

where

$$|\Delta k(\phi_1, \theta_P)| = 2\pi/L, \quad \phi_1 > \phi_0$$

$$|\Delta k(\phi_2, \theta_P)| = 2\pi/L, \quad \phi_2 < \phi_0$$

$$\Delta k(\phi_0, \theta_P) = 0.$$

α_{INT} is the angular aperture inside the crystal. Outside the crystal,

$$\alpha_{EX} = \left| \sin^{-1}[n^j(\omega_{IR}, \theta_P + \phi_1) \sin \phi_1] - \sin^{-1}[n^j(\omega_{IR}, \theta_P + \phi_2) \sin \phi_2] \right| \quad (10)$$

In this manner, each PM process can be characterized by the width of the $\Delta k(\phi)$ vs ϕ curve with θ_P fixed. Hence, the half-widths are defined as

$$HW_1 = \phi_0 - \phi_1 \quad (11)$$

and

$$HW_2 = \phi_0 - \phi_2. \quad (12)$$

The pump radiation always has a finite divergence, and hence the PM angles are not well defined. Variations in θ_P will give PM up-conversion for different values of ϕ ; hence the angular aperture is increased. The divergence Δ of the pump radiation inside the crystal is, however, less than that outside, i.e.,

$$\Delta_{INT} = \Delta_{EX}/\bar{n}(\omega_P) \quad (13)$$

where $\bar{n}$ is some average index of refraction.

The maximum angular aperture is obtained with NCPM. The aperture is the greatest if, in this case, Eqs. (4) and (7) are solved with $\Delta k = -2\pi/L$. This technique is discussed by Warner. However, a larger angular aperture does not always guarantee better resolution. To determine resolution, one must find the change in ϕ that will cause a variation in θ_S just equal to the width of θ_S values caused by the divergence of the pump radiation. A variation in θ_P due to a divergence of Δ causes a change in θ_S of

$$\gamma = \Delta + \sin^{-1} \left[\frac{k_{IR}}{k_S} \sin(\phi - \Delta) \right] - \sin^{-1} \left[\frac{k_{IR}}{k_S} \sin \phi \right] \quad (14)$$

This change in θ_S is equivalently produced by a change in ϕ (with θ_P fixed) of

$$\epsilon = \sin^{-1} \left\{ \frac{k_S}{k_{IR}} \sin \left[\Delta + \sin^{-1} \left(- \frac{k_{IR}}{k_S} \sin \Delta \right) \right] \right\} \quad (15)$$

Hence, the number of resolvable lines of IR is equal to

$$R = \alpha_{INT}/\epsilon \quad (16)$$

GENERAL DESCRIPTION OF THE PROGRAM

The program is written in Fortran IV language and, in the form given in Appendix A, has been run on a CDC 3800 computer. Input to the program is minimal and is on punched cards.

For each material to be analyzed, it is first necessary to fit dispersion data to a Sellmeier equation of the form

$$n_i^2 = A_i + B_i/(C_i - \lambda^2) - D_i\lambda^2, \quad (i = x, y, z) \quad (17)$$

(The program can easily be modified to use any other dispersion relation by modifying the function FIN (W, I), which is given in Table 1.) Besides the constants A_i , B_i , C_i , and D_i , it is necessary to supply the upper and lower wavelength limits of the transparent region of the crystal, the length of the crystal, and the range of values of the pump-source divergence to be considered. This information is given on a set of four data cards for each material. The required format is given in Table 2. The first data card gives the number of materials to be analyzed. Data cards 2 through 5 are repeated for each material. The symbols used for the data are defined in Table 3.

Pump wavelengths of 0.6943 μ and 1.06 μ have been selected, since they lie in or near the red part of the spectrum as discussed above, and intense laser sources are readily available at these wavelengths. The program analyzes up-conversion processes in which all three wavelengths lie in the region of transparency. The IR wavelength is scanned from the lower wavelength limit of transparency upward in equal increments on a logarithmic scale. The interval is determined in statement 10 of the main program.

Table 1
Subprograms

Name	Calculations	Line No. of Accuracy Test
FNK (XK, PP, DD)	Angle between k_p and z -axis for PM where XK = angle between k_p and k_{IR} PP = (see text) DD = value of Δk at PM (see text)	222
TNCPM (TCL, D)	Noncritical PM angle TCL = collinear PM angle D = value of Δk at PM	144
PVAR (T, P, DD, E)	Variation in ϕ for PM when θ_p is varied T, P = PM angles θ_p , ϕ DD = amount θ_p is increased E = value of Δk	178
FDK (T, P)	Δk T, P = PM angles θ_p , ϕ	—
HWDK (L, T, P, I)	Width of $\Delta k(\phi)$ vs ϕ curve L = length of crystal T, P = PM angles I = index to specify type of variation in ϕ to be performed	281
OUT	Printout routine	—
FIN (W, I)	Refractive index W = wavelength of desired index I = 1, 2, or 3 corresponding to x , y , or z optical axis	—
FN1 (A) FN2 (A) FN3 (A) }	Refractive index for arbitrary direction of propagation A = angle between direction of propagation and z axis	—
FN2C (Q) FN3C (Q) }	Refractive index squared for arbitrary direction of propagation Q = same as A in FN1 (A)	—

Table 2
Input Data Cards

Data Card Number	Format	Symbols
1	(I2)	N
2	(A5, 5X, 8F 10.1)	ANAME, UL, LL, L, DL, DU, DD
3	(4F 10.4)	AX, BX, CX, DX
4	(4F 10.4)	AY, BY, CY, DY
5	(4F 10.4)	AZ, BZ, CZ, DZ

Table 3
Definitions of Symbols

Symbol	Definition	Units
N	Number of materials to be analyzed	Integer
ANAME	Name of material	
UL, LL	Upper and lower wavelength limits for transparency	Angstrom
L	Length of crystal	Centimeter
AX, BX, ... DZ	Parameters for Sellmeier equation for indexes corresponding to x , y , and z optical axes. (For uniaxial crystal $z \rightarrow$ extraordinary polarization, $x = y \rightarrow$ ordinary polarization.)	

For each set of possible wavelengths, all polarization combinations are checked for a possible PM process. The output is labeled " $O + O = E$," etc. for (ordinary polarization) + (ordinary polarization) = (extraordinary polarization), etc. "Not Phasematchable" is printed if an orientation cannot be found for phase-matched up-conversion. If up-conversion at a given set of wavelengths is phase matchable, then all the parameters discussed in the previous section are calculated and printed (see Appendix B).

The functions of the various subprograms are listed in Table 1. In particular, the function FNX (X, P, D) is more general than need be for this program. FNX will calculate a PM angle for any orientation of k_{IR} with respect to k_P . In this case P is the angle between the (k_P, z -axis) plane and the (k_{IR}, z -axis) plane, and X is the angle between k_P and k_{IR} .

The various calculations are iterated until a predetermined accuracy is reached. The line numbers for the appropriate accuracy determining points in the program are listed in Table 1.

REFERENCES

1. Johnson, F.M., and Duardo, J.A., IEEE J. Quan. Elec. QE-2:296 (1966)
2. Midwinter, J.E., and Warner, J., J. Appl. Physics 38:519 (1967)
3. Miller, R.C., and Nordland, W.A., IEEE J. Quant. Electr. QE-3:642 (1967)
4. Yariv, A., "Quantum Electronics," New York:Wiley, 1967
5. Warner, J., "Opto-Electronics" 1:25 (Feb. 1969)

Appendix A

PROGRAM LISTING

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PROGRAM PHASMCH                                00000100
DATA (UP=57.2957795),(DN=.017453293),(CC=6.28318E8),(C1=1000.) 00000200
COMMON/1/W1,W2,W3                               /7/IN3/8/IN2/9/IN1/4/IX/10/PNC 00000300
1/11/K,TCL,TNCL,HWC1,HWC2,HWC1,HWC2,HWC3,HWC4,HWC3,HWC4,D,J,DIV00000400
2/12/EXHW1,EXHW2,EXW1,EXW2,EXHW5,EXHW6,FNL1,FNL2,PC1,PNC1,PC2 00000500
3      /5/HW1,HW2,E/1/AX,UX,CX,UX,AY,UY,CY,DY,AZ,BZ,CZ,DZ/2/K1 00000600
4      /8/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00000700
REAL LL,L,K1                                     00000800
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00000900
READ 99,N                                         00001000
DO 9 I1=1,N                                       00001100
50 READ 110,ANAME,UL,LL,L,DL,DU,DD,AX,BX,CX,DX,AY,BY,CY,DY,AZ,BZ,CZ, 00001200
1      DZ                                         00001300
DELK=6.28318/L                                  00001400
E=DELK/50.                                       00001500
DF=KK=2.5E-5/L                                  00001600
IZ1=(DU-DL)/DD+1.                               00001700
DO 15 IZZ=1,IZ1                                  00001800
DDD=DL+DD*(IZZ-1)                               00001900
PRINT 100,ANAME,UL,LL,L                        00002000
PRINT 102,DDD                                    00002100
PRINT 101,E,DELK,DELKK                         00002200
DO 1 I=1,2                                       00002300
W1=6943.                                         00002400
IF(I.EQ.2) W1=10600.                            00002500
NX1=FIN(W1,1)                                    00002600
NY1=FIN(W1,2)                                    00002700
NZ1=FIN(W1,3)                                    00002800
W2=LL                                             00002900
GO TO 11                                         00003000
10 W2=W2-W2/8.                                   00003100
IF(W2.LT.UL) GO TO 1                            00003200
11 W3=1./(1./W1+1./W2)                           00003300
IF(W1.GT.LL.OR.W1.LT.UL.OR.W2.GT.LL.OR.W2.LT.UL.OR.W3.GT.LL.OR.W3 00003400
;      .LT.UL) GO TO 10                         00003500
NX2=FIN(W2,1)                                    00003600
NY2=FIN(W2,2)                                    00003700
NZ2=FIN(W2,3)                                    00003800
NX3=FIN(W3,1)                                    00003900
NY3=FIN(W3,2)                                    00004000
NZ3=FIN(W3,3)                                    00004100
DIV=DDD/((NX1+NZ1)/2.)                          00004200
D=ASIN((W2/W3)*SIN(DIV +ASIN((W3/W2)*SIN(-DIV))))*C1 00004300
DO 4 K=1,6                                       00004400
IF(K.GT.3) GO TO 6                              00004500
3 IN3=2                                           00004600
IN1=1                                             00004700
IN2=1                                             00004800
IF(K.EQ.2) IN1=2                                 00004900
IF(K.EQ.3) IN2=2                                 00005000
GO TO 12                                         00005100
6 IN3=1                                           00005200
IN1=2                                             00005300
IN2=2                                             00005400
IF(K.EQ.5) IN1=1                                 00005500
IF(K.EQ.6) IN2=1                                 00005600
12 J=1                                           00005700
TCL=FNX(0.,0.,0.)                               00005800
IF(IX.GT.1) GO TO 5                             00005900

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CALL HWDK(L,TCL,0.,4)                                00006000
IF(IX.GT.1) GO TO 5                                    00006100
HWC1=HW1*C1                                             00006200
HWC2=HW2*C1                                             00006300
FN=FN2(TCL)                                             00006400
EXHW1=ASIN(SIN(HW1)*FN)*C1                             00006500
EXHW2=ASIN(SIN(HW2)*FN)*C1                             00006600
PC1=PVAR(TCL,0.,DIV/2.,0.)                             00006700
PC2=PVAR(TCL,0.,-DIV/2.,0.)                             00006800
CALL HWDK(L,TCL+DIV/2.,PC1,6)                         00006900
HWC3=HW2                                                00007000
CALL HWDK(L,TCL-DIV/2.,PC2,5)                         00007100
HWC4=HW1                                                00007200
A1=DIV/2.+ABS(PC1+HWC3)                                00007300
A2=DIV/2.+ABS(PC2+HWC4)                                00007400
FN=FN2(TCL)                                             00007500
EXW1=ABS(ASIN(SIN(A1)*FN)+ASIN(SIN(A2)*FN))*C1        00007600
HWC3=HWC3*C1                                           00007700
HWC4=HWC4*C1                                           00007800
FNL1=(A1+A2)*C1/D                                     00007900
DQ=0.                                                  00008000
7 TNCL=TNCPM(TCL,DQ)                                   00008100
CALL HWDK(L,TNCL,PNC,3)                               00008200
HWC1=HW1*C1                                             00008300
HWC2=HW2*C1                                             00008400
FN=FN2(TNCL+PNC)                                       00008500
EXHW5=ASIN(SIN(HW1)*FN)*C1                             00008600
EXHW6=ASIN(SIN(HW2)*FN)*C1                             00008700
IF(J.EQ.2) GO TO 8                                    00008800
CALL OUT                                              00008900
J=2                                                    00009000
DQ=DELK                                                00009100
TCL=FNX(0.,0.,DQ)                                     00009200
GO TO 7                                                00009300
8 PNC1=PVAR(TNCL,PNC,DIV,DELK)                        00009400
CALL HWDK(L,TNCL+DIV,PNC1,3)                         00009500
HWC3=HW1                                                00009600
HWC4=HW2                                                00009700
FN=FN2(TNCL+PNC)                                       00009800
EXW2=ABS(ASIN(SIN(HWC3)*FN)-ASIN(SIN(HWC4)*FN))*C1    00009900
HWC3=HWC3*C1                                           00010000
HWC4=HWC4*C1                                           00010100
FNL2=ABS(HWC3-HWC4)/D                                 00010200
5 CALL OUT                                             00010300
4 CONTINUE                                             00010400
2 GO TO 10                                             00010500
1 CONTINUE                                             00010600
15 CONTINUE                                            00010700
9 CONTINUE                                             00010800
99 FORMAT(12)                                          00010900
100 FORMAT(20X,21H*** UP-CONVERSION IN .A5.4H ***//39H THE SHORTEST WA00011000
1VELENGTH TRANSMITTED IS .F10.2/38H THE LONGEST WAVELENGTH TRANSMIT00011100
2TED IS .F10.2/25H THE LENGTH OF CRYSTAL IS .F10.2,2X,3HCM./ 90H AL00011200
3L PHASE MATCH ANGLES ARE IN DEGREES, P.M. ANGLES ARE MEASURED BETW00011300
4EEN THE Z-AXIS AND K1 /33H TCL = COLINEAR PHASE MATCH ANGLE /37H T00011400
5NCL = NONCRITICAL PHASE MATCH ANGLE /49H PNC = ANGLE BETWEEN (K1,K00011500
62) FOR NONCRITICAL P.M. /36H ALL HALFWIDTHS ARE IN MILLIRADIANS / 00011600
77H HWC = HALFWIDTH OF DELK VS. THETA CURVE MEASURED BETWEEN MAX. 00011700
8AND FIRST ZERO/39H HWNC = HALFWIDTH FOR NONCRITICAL P.M. ) 00011800

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102 FORMAT( 68H PC1,PC2 = PC1 FOR TCL = TCL+OR-DIV/2, THE INTERNAL DIV00011900
    DIVERGENCE OF W1 / 31H PNC1 = PNC FOR TNCL = TNCL+DIV / 32H EW = EXTE00012000
    2RNAL ANGULAR APERATURE / 32H R = NUMBER OF RESOLVEABLE LINES / 00012100
    349H EXTERNAL DIVERGENCE (FULL ANGLE) OF PUMP BEAM = .F6.4) 00012200
101 FORMAT(46H HWC AND HWNC ARE MEASURED WITH TCL/TNCL FIXED /19H DELT00012300
    1A K IS WITHIN .F7.3,15H 1/CM. OF 2P1/L/9H 2P1/L = .F7.3,5X,24H (2P00012400
    21/L)/K3 IS APPROX = .E10.3/46H K1,K2, AND K3 ARE COPLANER IN THE (00012500
    3Y,Z) PLANE /37H E POLARIZATION IS IN THE (Y,Z) PLANE /41H O POLARI00012600
    4ZATION IS OUT OF THE (Y,Z) PLANE /69H FOR UNIAXIAL CRYSTALS THE Z-00012700
    5AXIS = C-AXIS. NZ = NE, AND NX = NY = NO /26H * INDICATES DELTA K 00012800
    6= 2P1/L /56H W1,W2,W3 CORRESPOND TO PUMP, IR, AND SIGNAL WAVELENGT00012900
    7HS /55H NX,NY,NZ ARE REFRACTIVE INDICES FOR X,Y,Z OPTICAL AXIS //500013000
    89H ALL POSSIBLE UP-CONVERSION PROCESSES ARE LISTED BELOW ----//00013100
110 FORMAT(A5,5X,6F10,1/4F10,4/4F10,4/4F10,4) 00013200
    END 00013300
    FUNCTION TNCPM(TCL,D) 00013400
    COMMON /10/P 00013500
    T=TCL 00013600
    DP=0.05 00013700
    5 T1=FNX(DP,3,14159,D) 00013800
      IF(T1,LT,T) GO TO 10 00013900
      DP=-DP 00014000
      T1=FNX(DP,3,14159,D) 00014100
      IF(T1,LT,T) GO TO 10 00014200
      DP=DP/10. 00014300
      IF(ABS(DP),LT,0.00001) GO TO 21 00014400
      GO TO 5 00014500
    10 T=T1 00014600
      P=DP 00014700
    14 T1=FNX(P+DP,3,14159,D) 00014800
      IF(T1,LT,T) GO TO 12 00014900
      P=P+DP 00015000
      DP=-DP/4. 00015100
      IF(ABS(DP),LT,0.0001) GO TO 20 00015200
      T=T1 00015300
      GO TO 14 00015400
    12 P=P+DP 00015500
      T=T1 00015600
      GO TO 14 00015700
    20 TNCPM=T1 00015800
      RETURN 00015900
    21 TNCPM=T1 00016000
      P=DP 00016100
      RETURN 00016200
    END 00016300
    FUNCTION PVAR(T,P,DD,E) 00016400
    COMMON/1/W1,W2,W3/2/K1 00016500
    REAL K1 00016600
    D=.001 00016700
    IF(DD.GT,0.0) D=-D 00016800
    PP=P 00016900
    T1=T+DD 00017000
    K1=6.28318E8*FN1(T1)/W1 00017100
    1 PP=PP+D 00017200
    2 X1=ABS(FDK(T1,PP)+E) 00017300
    X2=ABS(FDK(T1,PP+D)+E) 00017400
    IF(X2,LT,X1) GO TO 1 00017500
    PP=PP+D 00017600
    D=-D/5.0 00017700

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      IF (ABS(D).LT.1E-5) GO TO 10
      GO TO 2
10  PVAR=PP
      RETURN
      END
      FUNCTION FNX(XX,PP,DD)
      DATA (E=1,E=6)
      COMMON/1/W1,W2,W3
      FK(Q,A)=SQRT((FN1(A)/W1)**2+FN2C(Q)/(W2*W2)-2.*FN1(A)*
1   SQRT(FN2C(Q))*CXX/(W1*W2))
      D=DD/6.28318E8
      P=PP
      X=XX
      IF (XX.GT.0) GO TO 20
      X=-X
      P=3.14159274+PP
20  IKX=1JX=0
      D1=ABS(XP-XX)
      XP=XX
      CX=COS(X)
      SX=SIN(X)
      CXX=COS(3.1415927-X)
      CP=COS(P)
      IF (R.LT.0.07.OR.R.GE.1.57) R=0.07
      IF (D1.LT.100.*E) D1=100.*E
      IF (D1.GT.0.1) D1=0.1
      IF (R.EQ.0.07) D1=0.1
1   IKX=IKX+1
      IF (IKX.GT.100) GO TO 5
      RD=R+D1
      CR=COS(R)
      SR=SIN(R)
      CRD=COS(RD)
      SRD=SIN(RD)
      C2=CR*CX+SR*SX*CP
      C5=CRD*CX+SRD*SX*CP
      Y1=FK(C2,R)
      Y2=FK(C5,RD)
      C3=(FN1(R)/W1-CXX*SQRT(FN2C(C2))/W2)/Y1
      C4=(FN1(RD)/W1-CXX*SQRT(FN2C(C5))/W2)/Y2
      C6=C3*CR+SR*SQRT(ABS(1.-C3*C3))*CP
      C7=C4*CRD+SRD*SQRT(ABS(1.-C4*C4))*CP
      Y=ABS(SQRT(FN3C(C6))/W3+D-Y1)
      Z=ABS(SQRT(FN3C(C7))/W3+D-Y2)
      IF (ABS(D1).LT. E ) GO TO 2
      IF (IKX.EQ.1) GO TO 10
      IF (Y.GT.Z) GO TO 3
      D1=-D1/10
      R=R-10*D1
      GO TO 1
3   R=R+D1
      IF (R.LT.0.0.OR.R.GE.1.6 ) GO TO 12
      GO TO 1
2   FNX=R
      IF (C6.LT.0.) 1JX=2
      RETURN
10  IF (Z.GT.Y) D1=-D1
      IF (Z.GT.Y) GO TO 1
      GO TO 3

```

```

00017800
00017900
00018000
00018100
00018200
00018300
00018400
00018500
00018600
00018700
00018800
00018900
00019000
00019100
00019200
00019300
00019400
00019500
00019600
00019700
00019800
00019900
00020000
00020100
00020200
00020300
00020400
00020500
00020600
00020700
00020800
00020900
00021000
00021100
00021200
00021300
00021400
00021500
00021600
00021700
00021800
00021900
00022000
00022100
00022200
00022300
00022400
00022500
00022600
00022700
00022800
00022900
00023000
00023100
00023200
00023300
00023400
00023500
00023600

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```

12 IF(IJX.GT.0) GO TO 6
14 IJX=1
   R=0.07
   O1=0.1
   IKX=1
   GO TO 1
6 IJX=2
   R=0.0
   RETURN
5 IF(IJX.GT.0) GO TO 8
   GO TO 14
8 PRINT 144,X,P,R
   IJX=2
   FN=R
144 FORMAT(10H FN ERROR .5X,3HX = ,F9.4,5X,3HP = ,F9.4,5X,3HR = ,F9.4)
   RETURN
   END
   FUNCTION FDK(T,P)
   COMMON /1/W1,W2,W3/2/K1
   REAL K2,K2S,K2C,K3,K1
   DATA (C1=6.28318E8)
   K2=C1*FN2(T+P)/W2
   K2S=K2*SIN(P)
   K2C=K2*COS(P)
   P3=ATAN(K2S/(K1+K2C))
   K3=C1*FN3(T+P3)/W3
   FDK=K3-SQRT(K2S**2+(K2C+K1)**2)
   RETURN
   END
   SUBROUTINE HWDK(L,T,P,1)
   REAL L,L2,K1
   DATA (CC=6.28318E8)
   COMMON /1/W1,W2,W3 /2/K1/5/V1,V2,E/4/IX
   K1=CC*FN1(T)/W1
   L2= 6.28318/L
   IF(ABS(FDK(T,P)).GT.L2*1.5 ) GO TO 30
   DV=0.01
   IF(1.EQ.2.OR.1.EQ.6) DV=-.01
1 V=DV
2 DK=FDK(T,P+V)
   IF(1.GT.3) DK=ABS(DK)
   IF(ABS( DK -L2).LT.E) GO TO 20
   IF( DK .LT.L2) GO TO 10
   DV=DV/10.
   IF(ABS(DV).LT.1E-6) GO TO 31
   V=V-DV*9.
   GO TO 2
10 V=V+DV
   GO TO 2
20 IF(DV.LT.0.) GO TO 25
   DV=-0.01
   V1=V
   IF(1.EQ.1.OR.1.EQ.5) GO TO 25
   GO TO 1
25 V2=V
   RETURN
30 IX=2
31 PRINT 100,T,P,L2
100 FORMAT(3F15.5)

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RETURN                                00049600
END                                  00049700
SUBROUTINE OUT                        00049800
COMMON/1/W1,W2,W3                    /4/IX/!0/PN 00049900
1/11/K,TC,TNC,HW1,HW2,HWN1,HWN2,HW3,HW4,HWN3,HWN4,OU,J,DV 00050000
2/12/EHW1,EHW2,EXW1,EXW2,EHW5,EHW6,FNL1,FNL2,PCL1,PCL2 00050100
3 /6/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00050200
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00050300
DATA (UP=57.2957795),(DN=.017453293) 00050400
IF(K.GT.1.OR.J.GT.1) GO TO 5         00050500
DIV=DV*1000.                         00050600
1 PRINT 100,W1,W2,W3,NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3,OU,DIV 00050700
5 IF(IX.GT.1) GO TO 10               00050800
TCL=TC*UP                            00050900
PC1=PCL1*UP                          00051000
PC2=PCL2*UP                          00051100
TNCL=TNC*UP                          00051200
PNC=PN*UP                            00051300
PNC1=PNCL1*UP                       00051400
IF(J.EQ.2) GO TO 3                   00051500
GO TO (11,12,13,14,15,16),K        00051600
11 PRINT 110,TCL,HW1,HW2,EHW1,EHW2,TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00051700
RETURN                                00051800
12 PRINT 120,TCL,HW1,HW2,EHW1,EHW2,TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00051900
RETURN                                00052000
13 PRINT 130,TCL,HW1,HW2,EHW1,EHW2,TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00052100
RETURN                                00052200
14 PRINT 140,TCL,HW1,HW2,EHW1,EHW2,TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00052300
RETURN                                00052400
15 PRINT 150,TCL,HW1,HW2,EHW1,EHW2,TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00052500
RETURN                                00052600
16 PRINT 160,TCL,HW1,HW2,EHW1,EHW2,TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00052700
RETURN                                00052800
10 GO TO (21,22,23,24,25,26),K      00052900
21 PRINT 210                          00053000
RETURN                                00053100
22 PRINT 220                          00053200
RETURN                                00053300
23 PRINT 230                          00053400
RETURN                                00053500
24 PRINT 240                          00053600
RETURN                                00053700
25 PRINT 250                          00053800
RETURN                                00053900
26 PRINT 260                          00054000
RETURN                                00054100
3 PRINT 170,                          TNCL,PNC,HWN1,HWN2,EHW5,EHW6 00054200
PRINT 200,PC1,PC2,HW3,HW4,EXW1,FNL1,PNC1,HWN3,HWN4,EXW2,FNL2 00054300
IF(K.EQ.6) GO TO 4                   00054400
RETURN                                00054500
4 PRINT 300                          00054600
RETURN                                00054700
100 FORMAT(6H W1 = ,F10.2,10X,5HW2 = ,F10.2,10X,5HW3 = ,F10.2,10X,516H 00054800
1 NX = ,F10.4,9X)/3(6H NY = ,F10.4,9X)/3(6H NZ = ,F10.4,9X)// 00054900
25X, 35HINTERNAL RESOLUTION LIMIT (MRAD) = ,F7.4, 00055000
3 5X, 16HINTERNAL DIV. = ,F6.4//) 00055100
110 FORMAT(9H O+0=E---,7H TCL = , F7.4,2X,6HHWC = ,4F6.1,2X,7HTNCL = ,00055200
1 F7.4,2X,6HPNC = , F7.4,2X,7HHWNC = ,4F6.1) 00055300
120 FORMAT(9H E+0=E---,7H TCL = , F7.4,2X,6HHWC = ,4F6.1,2X,7HTNCL = ,00055400

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1      F7.4,2X,6HPNC = F7.4,2X,7HHWNC = .4F6.1)      00035300
130 FORMAT(9H 0+E=E---,7H TCL = , F7.4,2X,6HHWC = .4F6.1,2X,7HTNCL = ,00035600
1      F7.4,2X,6HPNC = F7.4,2X,7HHWNC = .4F6.1)      00035700
140 FORMAT(9H E+E=0---,7H TCL = , F7.4,2X,6HHWC = .4F6.1,2X,7HTNCL = ,00035800
1      F7.4,2X,6HPNC = , F7.4,2X,7HHWNC = .4F6.1)      00035900
150 FORMAT(9H 0+E=0---,7H TCL = , F7.4,2X,6HHWC = .4F6.1,2X,7HTNCL = ,00036000
1      F7.4,2X,6HPNC = , F7.4,2X,7HHWNC = .4F6.1)      00036100
160 FORMAT(9H E+0=0---,7H TCL = , F7.4,2X,6HHWC = .4F6.1,2X,7HTNCL = ,00036200
1      F7.4,2X,6HPNC = , F7.4,2X,7HHWNC = .4F6.1)      00036300
170 FORMAT(9H * , 4X, , 7HTNCL = ,00036400
1      F7.4,2X,6HPNC = , F7.4,2X,7HHWNC = .4F6.1)      00036500
200 FORM (10X,5HPC1 =,F7.4,6H PC2 =,F7.4,5H HW =,2F6.1,4H EW=,F6.1, 00036600
1      3H R=,F6.1,7H PNC1 =,F7.4,5H HW =,2F6.1,4H EW=,F6.1,3H R=,F6.1) 00036700
210 /FORMAT(9H 0+0=E---,10X,28H*** NOT PHASE MATCHABLE *** ) 00036800
220 FORMAT(9H E+0=E---,10X,28H*** NOT PHASE MATCHABLE *** ) 00036900
230 FORMAT(9H 0+E=E---,10X,28H*** NOT PHASE MATCHABLE *** ) 00037000
240 FORMAT(9H E+E=0---,10X,28H*** NOT PHASE MATCHABLE *** ) 00037100
250 FORMAT(9H 0+E=0---,10X,28H*** NOT PHASE MATCHABLE *** ) 00037200
260 FORMAT(9H E+0=C---,10X,28H*** NOT PHASE MATCHABLE *** //39(3H *) 00037300
1      //) 00037400
300 FORMAT(//30(3H *)//) 00037500
END 00037600
FUNCTION FIN(W,1) 00037700
COMMON/13/AX,BX,CX,DX,AY,BY,CY,DY,AZ,BZ,CZ,DZ 00037800
X=WWW*1.0E-8 00037900
GO TO (1,2,3),1 00038000
1 FIN=SQRT(AX+BX/(X-CX)-DX*X) 00038100
RETURN 00038200
2 FIN=SQRT(AY+BY/(X-CY)-DY*X) 00038300
RETURN 00038400
3 FIN=SQRT(AZ+BZ/(X-CZ)-DZ*X) 00038500
RETURN 00038600
END 00038700
FUNCTION FN1(A) 00038800
COMMON /1/W1,W2,W3 /9/IN1 00038900
4 /6/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00039000
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00039100
GO TO (1,2),IN1 00039200
1 FN1=NX1 00039300
RETURN 00039400
2 FN1=1./SQRT((COS(A)/NY1)**2+(SIN(A)/NZ1)**2) 00039500
RETURN 00039600
END 00039700
FUNCTION FN2(A) 00039800
COMMON /1/W1,W2,W3/8/IN2 00039900
4 /6/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00040000
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00040100
GO TO (1,2),IN2 00040200
1 FN2=NX2 00040300
RETURN 00040400
2 FN2=1./SQRT((COS(A),NY2)**2+(SIN(A)/NZ2)**2) 00040500
RETURN 00040600
END 00040700
FUNCTION FN3(A) 00040800
COMMON /1/W1,W2,W3/7/IN3 00040900
4 /6/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00041000
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3 00041100
GO TO (1,2),IN3 00041200
1 FN3=NX3 00041300

```

RETURN	00041400
2 FN3=1./SQRT((COS(A)/NY3)**2+(SIN(A)/NZ3)**2)	00041500
RETURN	00041600
END	00041700
FUNCTION FN2C(Q)	00041800
COMMON /1/W1,W2,W3/8/IN2	00041900
4 /6/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3	00042000
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3	00042100
GO TO (1,2),IN2	00042200
1 FN2C=NX2*NX2	00042300
RETURN	00042400
2 FN2C=1./((Q/NY2)**2+(1.-Q*Q)/NZ2**2)	00042500
RETURN	00042600
END	00042700
FUNCTION FN3C(Q)	00042800
COMMON /1/W1,W2,W3/7/IN3	00042900
4 /6/NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3	00043000
REAL NX1,NX2,NX3,NY1,NY2,NY3,NZ1,NZ2,NZ3	00043100
GO TO (1,2),IN3	00043200
1 FN3C=NX3*NX3	00043300
RETURN	00043400
2 FN3C=1./((Q/NY3)**2+(1.-Q*Q)/NZ3**2)	00043500
RETURN	00043600
END	00043700

Appendix B
SAMPLE INPUT DATA AND PROGRAM OUTPUT

1	1.0	.001	.001
135000.	1.0	.001	.001
6.9445	.135665	.00192511	
6.9445	.135665	.00192511	
8.39218	.138793	.00266768	

*** UP-CONVERSION IN MCS ***

THE SHORTEST WAVELENGTH TRANSMITTED IS 6370.00
 THE LONGEST WAVELENGTH TRANSMITTED IS 145000.00
 THE LENGTH OF CRYSTAL IS 1.00 CM.
 ALL PHASE MATCH ANGLES ARE IN DEGREES, P.M. ANGLES ARE MEASURED BETWEEN THE Z-AXIS AND M1
 TOL = CELLULAR PHASE MATCH ANGLE
 TNCU = NONCRITICAL PHASE MATCH ANGLE
 PNC = ANGLE BETWEEN (M1,K2) AND NONCRITICAL P.M.
 ALL WAVELENGTHS ARE IN MILLIMETERS
 WMC = WAVELENGTH OF DELTA VS. THETA CURVE MEASURED BETWEEN PAX. AND FIRST ZERO
 WMCU = WAVELENGTH FOR NONCRITICAL P.M.
 PC1,PC2 = P1 FOR TOL = TOL*EM-DIV/2, THE INTERNAL DIVERGENCE OF M1
 PNC1 = PNC FOR TNCU = TNCU*EM
 EM = EXTERNAL ANGULAR AFFLUENCE

R = NUMBER OF RESOLVABLE LINES
 EXTERNAL DIVERGENCE (FULL ANGLE) OF PUMP BEAM = 0.0010
 WMC AND WMCU ARE MEASURED WITH TOL/TNCU FIXED
 DELTA K IS WITHIN 0.126 1/CM. OF 2PI/L
 2PI/L = 6.283 1/CM. IS APPROX = 2.500-005
 K1,K2, AND K3 ARE COPLANAR IN THE (Y,Z) PLANE
 POLARIZATION IS IN THE (Y,Z) PLANE
 PHASE MATCHING IS EITHER THE (Y,Z) PLANE
 FOR UNIAXIAL CRYSTALS THE Z-AXIS = C-AXIS. Y = NE. AND NX = NY = NB

* INDICATES DELTA K = 2PI/L
 M1,M2,M3 CORRESPOND TO PUMP, IR, AND SIGNAL WAVELENGTHS
 NX,NY,NZ ARE REFRACTIVE INDICES FOR X,Y,Z OPTICAL AXIS

ALL POSSIBLE UP-CONVERSION PROCESSES ARE LISTED BELOW ----

NOT REPRODUCED

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A Fortran computer program has been developed which analyzes a nonlinear material to determine (a) the range of IR wavelengths that can be converted in a phase matched (PM) process, (b) the PM orientation of the wave vectors for critical and noncritical PM, (c) the angular aperture for PM conversion, and (d) the maximum number of resolvable lines for image conversion. These characteristics are determined as a function of IR wavelength for a given pump wavelength, pump radiation divergence, and length of nonlinear crystal.			

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