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

R. A. Andrews
Quantum Optics Branch
Optical Sciences Division

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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

NRL Problem N01-14
Project XF-52545002-8083

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 \( \omega_{IR} \) is mixed with intense light of frequency \( \omega_p \), 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., \( (k_p + k_{IR}) = k_S \).

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 \( \omega_{IR} \) for PM up-conversion can be determined. Then for each set of frequencies \( \omega_p, \omega_{IR}, \) and \( \omega_S \), 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 \( \omega_{IR} \), 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

\[
\omega_p + \omega_{IR} = \omega_S
\]  

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

$$\Delta k = |\Delta k| = |k_P + k_{IR} - k_S| \leq \frac{2\pi}{L},$$

where for convenience we assume that $\Delta k$ is measured along the direction of $k_S$ 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:

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

where

$\phi = \text{angle between } k_P \text{ and } k_{IR}$

$\rho = \text{angle between } k_P \text{ and } k_S$

$\theta_T = \text{angle between the } Z\text{-axis and } k_t(t = P, IR, S)$

$i, j, k = 0 \text{ or } 1 \text{ for extraordinary or ordinary polarization}$

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
\[ n^0(\omega, \theta) = n_{\omega}(\omega) \] (5)

and

\[ n^p(\omega, \theta) = \left( \frac{\sin^2 \theta + \cos^2 \theta}{(n_p(\omega))^2 + (n_s(\omega))^2} \right)^{-1/2}, \] (6)

where \( n_s, n_p, \) and \( n_s \) are the refractive indexes for light polarized along the \( x, y, \) and \( z \) directions.

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

\[ \left( \frac{\partial \Delta k(\phi, \phi)}{\partial \phi} \right)_{\phi_p} = 0 \] (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 \( \phi \) for which IR light will be up-converted. This range defines the angular aperture \( \alpha \) for \( k_{12} \) and is defined by all values of \( \phi \) such that for a fixed value of \( \theta_p, \)

\[ \Delta k(\phi, \theta_p) < 2\pi/L \] (8)

or

\[ \alpha = |\phi_1 - \phi_2|, \] (9)

where

\[ |\Delta k(\phi_1, \theta_p)| = 2\pi/L, \quad \phi_1 > \phi_0 \]
\[ |\Delta k(\phi_2, \theta_p)| = 2\pi/L, \quad \phi_2 < \phi_0 \]
\[ \Delta k(\phi_0, \theta_p) = 0. \]

\( \phi_{1 \pi} \) is the angular aperture inside the crystal. Outside the crystal,

\[ \phi_{2 \pi} = \left[ \arcsin \left[ \frac{n'(\omega_{IR}, \theta_p + \phi_1) \sin \phi_1}{n'=(\omega_{IR}, \theta_p + \phi_2) \sin \phi_2} \right] \right. \] (10)

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

\[ HW_1 = \phi_0 - \phi_1 \] (11)

and

\[ HW_2 = \phi_0 - \phi_2. \] (12)

The pump radiation always has a finite divergence, and hence the PM angles are not well defined. Variations in \( \theta_p \) will give PM up-conversion for different values of \( \phi; \) hence the angular aperture is increased. The divergence \( \Delta \) of the pump radiation inside the crystal is, however, less than that outside, i.e.,
\[ \Delta_{INT} = \Delta_{IR}/\bar{n}(\omega_p) \]  

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 \( \phi \) that will cause a variation in \( \theta_s \), just equal to the width of \( \theta_s \) values caused by the divergence of the pump radiation. A variation in \( \theta_p \) due to a divergence of \( \Delta \) causes a change in \( \theta_s \) of

\[ y = \Delta + \sin^{-1}\left(\frac{k_{IR}}{k_S} \sin (\phi - \Delta)\right) - \sin^{-1}\left(\frac{k_{IR}}{k_S} \sin \phi\right). \]  

This change in \( \theta_s \) is equivalently produced by a change in \( \phi \) (with \( \theta_p \) fixed) of

\[ c = \sin^{-1}\left(\frac{k_S}{k_{IR}} \sin \left[\Delta + \sin^{-1}\left(\frac{k_{IR}}{k_S} \sin \Delta\right)\right]\right). \]

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

\[ R = a_{INT}/c \]

**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

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

(The program can easily be modified to use any other dispersion relation by modifying the function FIN (W, N), 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 \( \mu \) and 1.06 \( \mu \) 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

<table>
<thead>
<tr>
<th>Name</th>
<th>Calculations</th>
<th>Line No. of Accuracy Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNX (XX, PP, DD)</td>
<td>Angle between k&lt;sub&gt;p&lt;/sub&gt; and z-axis for PM where XX = angle between k&lt;sub&gt;p&lt;/sub&gt; and k&lt;sub&gt;k&lt;/sub&gt;, PP = (see text), DD = value of Δk at PM (see text)</td>
<td>222</td>
</tr>
<tr>
<td>TNCPM (TCL, D)</td>
<td>Noncritical PM angle TCL = collinear PM angle D = value of Δk at PM</td>
<td>144</td>
</tr>
<tr>
<td>FVAR (T, P, DD, E)</td>
<td>Variation in ϕ for PM when θ&lt;sub&gt;p&lt;/sub&gt; is varied T, P = PM angles θ&lt;sub&gt;p&lt;/sub&gt;, ϕ DD = amount θ&lt;sub&gt;p&lt;/sub&gt; is increased E = value of Δk</td>
<td>178</td>
</tr>
<tr>
<td>FDK (T, P)</td>
<td>Δk T, P = PM angles θ&lt;sub&gt;p&lt;/sub&gt;, ϕ</td>
<td>-</td>
</tr>
<tr>
<td>HWDK (L, T, P, I)</td>
<td>Width of Δk(ϕ) vs ϕ curve L = length of crystal T, P = PM angles I = index to specify type of variation in ϕ to be performed</td>
<td>281</td>
</tr>
<tr>
<td>OUT</td>
<td>Printout routine</td>
<td>-</td>
</tr>
<tr>
<td>FIN (W, I)</td>
<td>Refractive index W = wavelength of desired index I = 1, 2, or 3 corresponding to x, y, or z optical axis</td>
<td>-</td>
</tr>
<tr>
<td>FN1 (A)</td>
<td>Refractive index for arbitrary direction of propagation A = angle between direction of propagation and z axis</td>
<td>-</td>
</tr>
<tr>
<td>FN2 (A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FN3 (A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FN2C (Q)</td>
<td>Refractive index squared for arbitrary direction of propagation Q = same as A in FN1 (A)</td>
<td>-</td>
</tr>
<tr>
<td>FN3C (Q)</td>
<td></td>
<td></td>
</tr>
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</table>
Table 2
Input Data Cards

<table>
<thead>
<tr>
<th>Data Card Number</th>
<th>Format</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(22)</td>
<td>N</td>
</tr>
<tr>
<td>2</td>
<td>(A5, 5X, 6F 10.1)</td>
<td>ANAME, UL, LL, L, DL, DU, DD</td>
</tr>
<tr>
<td>3</td>
<td>(4F 10.4)</td>
<td>AX, BX, CX, DX</td>
</tr>
<tr>
<td>4</td>
<td>(4F 10.4)</td>
<td>AY, BY, CY, DY</td>
</tr>
<tr>
<td>5</td>
<td>(4F 10.4)</td>
<td>AZ, BZ, CZ, DZ</td>
</tr>
</tbody>
</table>

Table 3
Definitions of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Number of materials to be analyzed</td>
<td>Integer</td>
</tr>
<tr>
<td>ANAME</td>
<td>Name of material</td>
<td></td>
</tr>
<tr>
<td>UL, LL</td>
<td>Upper and lower wavelength limits for transparency</td>
<td>Angstrom</td>
</tr>
<tr>
<td>L</td>
<td>Length of crystal</td>
<td>Centimeter</td>
</tr>
<tr>
<td>AX, BX, ... DZ</td>
<td>Parameters for Sellmeier equation for indexes corresponding to x, y, and z optical axes. (For uniaxial crystal z — extraordinary polarization, x = y — ordinary polarization.)</td>
<td></td>
</tr>
</tbody>
</table>

For each set of possible wavelengths, all polarization combinations are checked for a possible PM process. The output is labeled "0 + 0 = 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 \( k_F \) with respect to \( k_P \). In this case \( P \) is the angle between the \((k_P, z\text{-axis})\) plane and the \((k_F, z\text{-axis})\) plane, and \( X \) is the angle between \( k_P \) and \( k_F \).

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

Appendix A

PROGRAM LISTING

PROGRAM PHASMCH

DATA (UP=57.2957795), (ON=0.17453293), (CC=6.2831858), (C1=1000.)
COMMON /1/W, /W2, W3
/7/IN3/B/IN2/9/IN1/4/IX/10/PNC
2/12/X1/EAXW2/EAXW1/EXH6/EXH4/FNL1/FNL2/PC1/PC1/PC2
3 /5/HW1/HW2/E1/AUXUX/CAXUX/AYCY/DYAZUZC2Z/D2Z/2/K1
READ 999/N
READ 999/N
50 READ 110/ANAME/UL+LL+DL+UL+DD+AX+DK+CX+DX+AY+DY+CY+DY+AZ+UZ+CZ+
1 DZ
DELP=6.2831858
E=DELP/DU
OF=KK*Z-ZE-S/L
IX=(DU-DL)/DD+1
DO 15 IX=1,121
DDD=DL+DU*Z11
PRINT 100/ANAME/UL+LL+L
PRINT 102/DDD
PRINT 101/E+DELK/DEKK
DO 1 =1,2
W1=6943*
IF(1*EO.2) W1*10600*
NX1=FIN(W1+1)
NY1=FIN(W1+2)
NZ1=FIN(W1+3)
W2=LL
GO TO 11
10 W2=W2-W2/8*
IF(W1-UL/UL) GO TO 1
11 W1=W1+1+W2
IF(W1+GTULL) OR=W1+LTUL+OR=W2+GTLL+OR=W2+LTUL+OR=W3+GTLL+GR=W3
1 
+LT+UL) GO TO 10
NX2=FIN(W2+1)
NY2=FIN(W2+2)
NZ2=FIN(W2+3)
NX3=FIN(W3+1)
NY3=FIN(W3+2)
NZ3=FIN(W3+3)
DIV=DDD/(NX1+NZ1+2)*
D=ASIN(W2+W3)*ASIN(DIV+ASIN(W3+W2)*SIN(-DIV+1))01C1
DO 4 K=1,6
IF(KGT.3) GO TO 6
3 IN3=2
IN1=1
IN2=1
IF(K*EO.2) IN1=2
IF(K*EO.3) IN2=2
GO TO 12
6 IN3=1
IN1=2
IN2=2
IF(K*EO.5) IN1=1
IF(K*EO.6) IN2=1
GO TO 12
12 J=1
TCL=FXN(0*0+2.0)
IF(IFX+GT1) GO TO 5
CALL HWOK(L+TCL+0..+4)
IF(X GT 1) GO TO 5
HW1=HW1+1
HW2=HW2+1
FN#FN(TCL)
EXW1=ASIN(SIN(HW1)*FN)*C1
EXW2=ASIN(SIN(HW2)*FN)*C1
PC1=PV1T(TCL+0..+DIV/2.+0.)
PC2=PV1T(TCL+0..-DIV/2.+0.)
CALL HWOK(L+TCL+DIV/2.+PC1+6)
HC3=HC2
CALL HWOK(L+TCL+DIV/2.+PC2+5)
HW4=HW1
A1=DIV/2.+ABS(PC1+HC3)
A2=DIV/2.+ABS(PC2+HC4)
FN#FN(TCL)
EXW1=ABS(A1*FN)+ASIN(SIN(A2)*FN)*C1
HC3=HC3+HC3*C1
HW4=HW4+HC4*C1
FNL1=(A1+A2)*C1/D
DG=0.
7 TCL=TNCMP(TCL+DG)
CALL HWOK(L+TCL+PNC+3)
HWNC1=HW1
HWNC2=HW2
FN#FN(TNC+PNC)
EXW5=ASIN(SIN(HW1)*FN)*C1
EXW6=ASIN(SIN(HW2)*FN)*C1
IF(J.EQ.2) GO TO 8
CALL OUT
J=2
DG=DELIK
TCL=FNLK(0..+DG)
GO TO 7
8 PNC1=PV1T(TNC+PNC+DIV+DELIK)
CALL HWOK(L+TNC+DIV+PNC+1+3)
HWNC3=HW1
HWNC4=HW2
FN#FN(TNC+PNC)
EXW2=ABS(A1*FN)-ASIN(SIN(HWNC4)*FN)*C1
HWNC3=HWNC3+C1
HWNC4=HWNC4+C1
FNL2=ABS(HWNC3-HWNC4)/D
CALL OUT
4 CONTINUE
2 GO TO 10
1 CONTINUE
15 CONTINUE
9 CONTINUE
99 FORMAT(12)
100 FORMAT(20X,21H*** UP-CONVERSION IN +A5+4H ***/39H THE SHORTEST WAVELENGTH IS transmit
1VLENGTH TRANSMITTED IS F10.2/3BH THE LONGEST WAVELENGTH TRANSMIT0001100
2TED IS F10.2/2X3MH* /90H AL0001120
3L PHASE MATCH ANGLES ARE IN DEGREES; P=MC ANGLES ARE MEASURED M1TWO0011300
4EEN THE Z-AXIS AND K1 /33H TCL = COLINEAR PHASE MATCH ANGLE /37M TD00011400
5NL = NONCRITICAL PHASE MATCH ANGLE /49H PNC = ANGLE BETWEEN (K1+K2)/1800
6Z FOR NONCRITICAL P4M+36H ALL HALF WIDTHS ARE IN MILLIRADIANS /00011600
777H HWC = HALF WIDTH OF DELK VS. THETA CURVE MEASURED BETWEEN MAX00011700
8BAND FIRST ZERO/39H HWNC = HALF WIDTH FOR NONCRITICAL P4M+300011800
102 FORMAT(68H) PC1=PC2 = PC FOR TCL = TCL+DIV/2; THE INTERNAL DIV00011900
1 ENERGIE OF wi / 31H PNC1 = PNC FOR TNCL = TNCL+DIV / 32H Ew = EXTE00012000
3Rnal ANGULAR APERATURE / 32H R = NUMBER OF RESOLVEABLE LINES / 00012100
34H EXTERNAL DIVERGENCE (FULL ANGLE) OF PUMP BEAM = *F6.4) 00012200
101 FORMAT(16H) HWC AND HWNC ARE MEASURED WITH TCL/TNCL FIXED /19H DELT00012300
1A K IS WITHIN *F7.315H 1/CM. OF 2P1/L/9H 2P1/L = *F7.3;5X;24M (2P00012400
2/L)/X IS APPROX = *E10;3/46M K1xK2, AND K3 ARE COPLANAR IN THE 100012500
3Y/Z) PLANE /37H E POLARIZATION IS IN THE (Y,Z) PLANE /41H 0 POLARIZATION IS OUT OF THE (Y,Z) PLAN00012600
4IZ IS C-AXIS; NZ = NE, AND NX = NY = NO /26H * INDICATES DELTA K 00012700
6* 2P1/L /56H WINX,W2,W3 CORRESPOND TO PUMP, IR, AND SIGNAL WAVELENGTH00012800
7TH /55H NX,NY,NZ ARE REFRACTIVE INDICES FOR X,Y,Z OPTICAL AXIS //300013000
9 ALL POSSIBLE UP-CONVERSION PROCESSES ARE LISTED BELOW ----//00013100
110 FORMAT(165X,6F10.4/4F10.4/4F10.4) 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 20 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,0.00001) 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,PRE.E) 00016400
COMMON/1/W1,W2,W3,2/K1 00016500
REAL K1 00016600
D=0.01 00016700
IF(DD+GT,0.0) D=D 00016800
PP=P 00016900
T1=T+000 00017000
K1=6.28318E8*FN(T1)/W1 00017100
1 PP=PP+0 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+0 00017600
D=D+5.0 00017700
IF(ABS(D) < 1E-5) GO TO 10
GO TO 2
10 PVAR=PP
RETURN
END
FUNCTION FNX(XP,PP,OD)
DATA (E=1.6-6)
COMMON/I,W1,W2+W3
FK(1) = SORT((FN1(A)/W1)**2+FN2C1)//(W2*W2)-2.*FN1(A)*
I = SORT(FN2C1)**CXX/(W1*W2))
D=DD/6.28318E6
P=PP
X=XX
IF(XX+GT.0) GO TO 20
X=-X
P=14159274*PP
20 IKX=IKX+1
IF(IKX.FQ.I) GO TO 10
D1=ABS(XP-XX)
XP=XX
X=COS(X)
SX=SIN(X)
CXX=COS(3.1415927-X)
CP=COS(P)
IF(D1+LT.07 OR P.GE.1†57) R=0.07
IF(D1+LT.100 OR P.GE.1†57) D1=100.07
IF(D1+GT.01) D1=0.1
IF(P.GE.0.07) D1=0.1
1 IKX=IKX+1
IF((IKX+GT.100) GO TO 5
RD=R401
CR=COS(R)
SR=SIN(R)
CXX=CRD**SRD**CP
C5=CRD**CRD**SRD**CP
Y1=FNI(C5/RD)
Y2=FNI(C3/RD)
C3=(FN1(R)W1-CCX*SORT(FN2C1)/W2)Y1
C4=(FN1(RD)W1-CCX*SORT(FN2C1C5)/W2)Y2
C6=C3*C3+SRD*SORT(A31-3+C3)**CP
C7=C4*C4+SRD*SORT(A31-3+C4)**CP
Y=ABS(SORT(FN2C1C5)/W3D+Y1)
Z=ABS(SORT(FN2C1C7)/W3D+Y2)
IF (ABS(D1) < LT.1) GO TO 10
IF(IKX+FQ.11) GO TO 10
IF (YGT.Z) GO TO 3
D1=D1/10
R=R-100D1
GO TO 1
3 R=R+D1
IF(R GT 0 OR P.GE.1†6) GO TO 12
GO TO 1
2 FNX=R
1 IF(C6+LT.0.) IKX=2
RETURN
10 IF(ZGT.Y) D1=D1
IF(ZGT.Y) GO TO 1
GO TO 3

12 IF(IJX*GT.0) GO TO 6
14 IJX=1
   R=0.07
   D=0.1
   IKX=1
   GO TO 1
6  IJX=2
   R=0.0
   D=0.4
   RETURN
5 IF(IJX*GT.0) GO TO 6
   GO TO 14
8 PRINT 144,X,R,P
   IJX=2
   FNXR
144 FORMAT(10H FNX ERROR $,5X,3HX = $F9,4,5X,3HP = $F9,4,5X,3HR = $F9,4)
   RETURN
   END
FUNCTION FD(X,T,P)
   COMMON /1/W1*W2*W3/2/K1
   REAL K2,K2S,K2C,K1
   DATA (C1=6.28318E8)
   K2=C1*FN2(T)/W2
   K2S=K2*SIN(P)
   K2C=K2*COS(K1)
   RETURN
END
SUBROUTINE H=DK(L,T,P+1)
   DATA (CC=6.28318E8)
   COMMON /1/W1*W2*W3
   L2=6.28318/L
   IF(Abs(FD(X,T,P)+L2*1.5 ) GO TO 30
   DV=0.01
   IF(I*EQ.2.OR.I*EQ.6) DV=-0.01
   1 V=V+DV
   2 DK=FD(X,T+1)
      IF(I*GT.3) DK=ABS(DK)
      IF(Abs(DK +L2)+LT+E) GO TO 20
      IF(DK +L2+L2) GO TO 10
      DV=DV/10
      IF(Abs(DV)+LT+1.6) GO TO 31
      V=V-DV
      GO TO 2
   10 V=V+DV
   GO TO 2
   20 IF(DV+LT+0.1) GO TO 25
      DV=0.01
      V=V
      IF(I*EQ.1.OR.I*EQ.5) GO TO 25
   25 V=V
   RETURN
30 IKX=2
31 PRINT 100,X,P,L2
100 FORMAT(10H TESTEND )
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`FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00037500`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00037300`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00037200`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00037100`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00037000`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036900`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036800`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036700`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036600`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036500`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036400`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036300`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036200`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036100`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00036000`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035900`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035800`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035700`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035600`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035500`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035400`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035300`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035200`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035100`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00035000`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034900`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034800`

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`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034600`

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`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034300`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034200`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034100`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00034000`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033900`

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`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033700`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033600`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033500`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033400`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033300`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033200`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033100`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00033000`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032900`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032800`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032700`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032600`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032500`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032400`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032300`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032200`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032100`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00032000`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031900`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031800`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031700`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031600`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031500`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031400`

`1 FORMAT(9H 0E---H TLC = F7.4*2X.6HPNC = A*6.1) 00031300`
RETURN 00441400
2 FN3*1.+SQR((COS(A)/NY3)**2+(SIN(A)/NZ3)**2)
RETURN 00441500
END 00441600
FUNCTION FN2C(Q)
COMMON /1/W1,W2,W3/8/1N2
4 /6/NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3
REAL NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3
GO TO (1,2)+1N2 00441700
1 FN2C=NX2+NX2 00441800
RETURN 00441900
2 FN2C*1./(Q/NY2)**2+(1.-Q*Q1/NZ2**2)
RETURN 00442000
END 00442100
FUNCTION FN3C(Q)
COMMON /1/W1,W2,W3/7/1N3
4 /6/NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3
REAL NX1+NX2+NX3+NY1+NY2+NY3+NZ1+NZ2+NZ3
GO TO (1,2)+1N3 00442200
1 FN3C=NX3*NX3 00442300
RETURN 00442400
2 FN3C*1./(Q/NY3)**2+(1.-Q*Q1/NZ3**2)
RETURN 00442500
END 00442600
Appendix B

SAMPLE INPUT DATA AND PROGRAM OUTPUT
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R. A. ANDREWS

*** UP-CONVERSION IN HGS ***

THE SHORTEST WAVELENGTH TRANSMITTED IS 0.370.00
THE LONGEST WAVELENGTH TRANSMITTED IS 1.050.00
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 N1
TCL = CELLI 1/3 PHASE MATCH ANGLE
TNCL = N2/N3 CRITICAL PHASE MATCH ANGLE
PNC = N4 = LATERAL (LY) A. N4 CRITICAL P.M.
ALL PHASE MATCH ANGLES ARE IN MILLI-ALIANS
HNC = HALF-LENGTH OF DELTA VS. CURVE MEASURED BETWEEN MAX. AND FIRST ZER
HMM = HALF-LENGTH OF N2/N3 CRITICAL P.M.
PC1,PC2 = PC FOR TCL = TCL+1/3N2. THE INTERNAL DIVERGENCE OF N1
PNC1 = PC FOR TNCL = INCL = TILTED
EM = FAMILIAL AMINDELA APETEN
N = NUMBER OF REPEATABLE LINES
EXTERNAL DIVERGENCE (FULL ANGLE) OF PUMP BEAK = 0.010
WAVE AMPLITUDE MEASURED WITH TCL/TNCL FIXED
DELTA X IS WITHIN 0.125 DEG. OF z/2
2P/L = 0.243
12P1/LXAX IS APPROX. 2.500-005
K1, K2, AND K3 ARE COPLANAR IN THE (YZ) PLANE
E POLARIZATION IS IN THE (YZ) PLANE
O POLARIZATION IS IN THE (XY) PLANE
FOR UNIAXIAL CRYSTALS THE Z-AXIS IS C-AXIS, Z = NE, AND HX = N0 = NY
* INDICATES DELTA X = 2P/L
N1, N2, K3 CORRESPOND TO PUMP, IR, AND SIGNAL WAVELENGTHS
NX, NY, NZ ARE REFRACTIVE INDICES FOR X, Y, Z OPTICAL AXIS

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

** NOT REPRODUCIBLE **
NRL REPORT 6941

\[ W1 = 6943.0 \quad W2 = 139509.00 \quad W3 = 6984.39 \]
\[ Wx = 7.9244 \quad Wx = 2.5687 \quad Wx = 7.9568 \]
\[ Wt = 2.8444 \quad Wy = 0.5897 \quad Wy = 2.8568 \]
\[ Wt = 3.1561 \quad Wt = 2.0123 \quad Wt = 3.1544 \]

**INTERNAL RESOLUTION LIMIT (PMAD) = 6.4987**  **INTERNAL DIV. = 0.3542**

- **BBF**
  - ***N=1 PHASE MATCHABLE***
- **EEF**
  - ***N=1 PHASE MATCHABLE***
  - ***N=1 PHASE MATCHABLE***
  - ***N=1 PHASE MATCHABLE***

\[ TCL = 22.4185 \quad PM = 3.9503 \quad HH = 38.0 -32.0 \quad 99.4 -93.0 \]
\[ TNC = 22.4371 \quad PM = 3.9503 \quad HH = 52.0 -47.0 \quad 156.2 -143.0 \]
\[ TNC = 22.9686 \quad PM = 4.0593 \quad HH = 47.5 -46.0 \quad 122.5 -118.4 \]

\[ PC1 = 1.3670 \quad PC2 = 0.0423 \quad PC3 = 10.0 \quad E = 10.0 \quad PM = 1.9086 \quad HH = 9.1 -24.1 \quad E = 297.5 \quad R = 17.7 \]

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**NOTE**
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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