A Novel Approach to a PPM-Modulated Frequency-Doubled Electro-Optic Cavity-Dumped Nd:YAG Laser

D. L. Robinson
Communications Systems Research Section

This article describes a technique which can provide frequency doubling, with high efficiency, while cavity dumping a laser for pulse position M*-ary modulation while being used for an optical communication link. This approach uses a secondary cavity that provides feedback of the undoubled fundamental light, which is normally lost, into the primary cavity to be recirculated and frequency doubled. Specific operations of the electro-optic modulator and frequency-doubling crystal are described along with the overall modulation scheme and experimental setup.*

I. Introduction

For deep space communication, optical frequencies provide many advantages over presently used technologies. Higher data rates, less power and mass consumption, and smaller beam divergence are some of the benefits provided by laser communications. Current link analyses incorporate either a ground-based station or an Earth-orbiting spacecraft to send to, and receive optical signals from, the mission spacecraft. Design considerations require the transmitter on the spacecraft to consist of a pulse position M-ary (PPM) modulated frequency-doubled Nd:YAG laser operating at 0.532 μm. The anticipated range of communication rates for deep space is between 20 kbits/sec and 50 Mbits/sec (dependent on the range of the mission). If we assume M = 256, this corresponds to nominal laser repetition rates between 2.5 kHz and 6.3 MHz. To achieve these rates of modulation, Q-switching is utilized at the lower rates and cavity dumping is utilized for the higher rates. In this article, a unique design, which efficiently incorporates both cavity dumping and frequency doubling for deep space optical communication is described.

II. Technical Background

In laser Q-switching, lasing is held off by introducing loss into the resonator cavity while energy is pumped into and stored in the atomic population inversion. Once the desired inversion is attained, cavity losses are reduced to allow lasing. In this mode, it is possible to attain a single large pulse output from the laser. The frequency range of Q-switching extends up to 50-100 kHz [1], with no lower boundary. The upper repetition rate is limited by the finite time to repump the inversion in the gain medium of the laser. To extend the frequency further, cavity dumping must be used. In cavity dumping, energy is stored in the photon field instead of the atomic inversion. The photon field is generated between two mirrors of maximum reflectivity. To extract a pulse from the resonator, the beam is electro-optically or acousto-optically switched out of the main resonator. Repetition rates achievable with cavity dumping have been demonstrated between 125 kHz and 10 MHz [1]. The lower limit is reached when the photon field within the resonator is reduced to one photon after dumping the field. At this point, the beginning of the buildup is dependent on the statistical variance of spontaneous emission. Hence, if the cavity is dumped of all its energy, cavity dumping becomes unstable [1]. If the cavity is not dumped of all its energy, for example by inducing an incomplete polarization flip with the electro-optic modulator, this lower limit can be extended. The upper limit of cavity dumping is limited by the switching time of the modulator. To extend pulse rates beyond 10 MHz, a mode-locked laser must be used.

Additionally, frequency doubling of the laser radiation is often desired for efficient detection at the receiver. The frequency-doubling conversion efficiency is a function of the intensity in the nonlinear doubling crystal. As the intensity increases, the conversion efficiency also increases. Therefore, to maximize efficiency, intra-cavity doubling is desirable because photon flux levels are much higher inside the laser resonator. Techniques for intra-cavity doubling of Q-switched lasers are well known. However, intra-cavity frequency doubling/cavity dumping is less desirable since placing a frequency-doubling crystal in the primary cavity would reduce the stored energy in the laser resonator. Once the energy is frequency doubled it can no longer stimulate emission in the gain medium and, therefore, will not experience gain in the laser resonator. On the other hand, in external frequency doubling the fundamental wavelength that is undoubled is lost, resulting in lower conversion efficiency. Therefore, a scheme has been conceived that efficiently frequency doubles while cavity dumping. The doubling crystal is placed outside the resonator and a third mirror is used to recycle the undoubled light back into the primary resonator. Since output beam losses are low in cavity dumping, switching light electro-optically or acousto-optically out of the primary cavity maintains a high-intensity beam, resulting in efficient frequency doubling. The third mirror, M_3, placed at a right angle to the primary cavity and used in conjunction with a polarizing beam splitter (other angles with other types of polarizing prisms may be used), forms a secondary cavity with M_1, which reflects the undoubled 1.06-μm light back into the primary cavity (see Fig. 1). Care must be taken to match the spatial modes of both resonators. The following section describes, in more detail, this technique for semi-intra-cavity doubling while cavity dumping.

III. Design Configuration

A unique design has been conceived to incorporate both cavity dumping and frequency doubling while reusing the undoubled light. This scheme incorporates an electro-optic modulator; however, the overall concept can be applied to cavity dumping with an acousto-optic modulator as well. Two schematics of the optical design are illustrated in Figs. 1(a) and (b). As is normal for cavity dumping, a photon field is built up between two resonator mirrors, M_1 and M_2. As seen in Figs. 1(a) and (b), a polarizing beam splitter (PBS) is inserted in the primary optical path to polarize the initial beam horizontally. When the appropriate field has been realized, a transverse electric field is applied to the electro-optic modulator (EO) to induce a quarter-wave phase retardation to the beam. A double pass through the electro-optic modulator creates a half-wave phase shift resulting in a 90-degree rotation of the polarization which is then reflected by the PBS. Upon reflection, the beam is directed through a frequency doubler (FD) and reflected by M_3. By utilizing a type-I frequency doubler,[1] that portion of the beam that is doubled will be rotated 90 degrees, resulting in horizontally polarized light which will be transmitted through the polarizing beam splitter and coupled out of the resonator. If instead a type-II frequency doubler is utilized, the doubled portion of the beam is rotated only 45 degrees. Since part of this beam would be reflected back into the cavity, a dichroic beam splitter must be used to efficiently couple out the 0.532-μm portion of the beam. In either case, the undoubled light remains in the vertical polarization and is reflected back into the primary cavity. As long as an electric field is applied to the electro-optic modulator, this returned 1.06-μm light will be preserved and rotated back to the original horizontal polarization. When the desired output pulse width has been attained, typically 10–20 nsec, the electric field applied to the modulator is switched to zero allowing the photon field in the original cavity to build up once again to accommodate a second pulse.

IV. Experimental Setup

A standard 2-watt 1.06-μm laser was procured from General Photonics to provide the basic resonator cavity: pump cavity, Nd:YAG rod, mirror-mounting hardware, and overall structural support. Modifications to the basic laser design were necessary to obtain appropriate beam waists and mirror reflectivities within the laser cavity for frequency doubling and cavity dumping. Since the efficiency of frequency doubling increases proportionately with the optical intensity, a tightly focused beam within the doubling crystal is desirable. A second design limitation was the aperture size of the electro-optic modulator. To aid in the determination of the modifications, a computer program was written to analyze the spatial mode size within the laser resonator. Mirror curvatures were optimized until desired beam waists within the cavity were formed. In Fig. 2, a typical output from the optimizing pro-

[1] Type-I frequency doubling converts two horizontally (or two vertically) polarized photons to one vertically (or one horizontally) polarized photon. Type-II frequency doubling converts one vertically and one horizontally polarized photon to one vertically (or horizontally) polarized photon.

gram is shown. The diameter of the spatial mode is plotted versus the length of the resonator cavity. Labels M_1 and M_2 designate the two mirrors of the primary laser resonator, while R and EO denote the rod and the electro-optic modulator, respectively. Between the rod and the front mirror, M_2, a tight focus is formed. Likewise, when the modulator rotates the field's polarization causing the beam to be reflected by the PBS into the secondary cavity formed by M_3, the beam will be tightly focused in the doubling crystal.

To maintain a low half-wave voltage on the electro-optic modulator, a $LiNbO_3$ or $LiTaO_3$ crystal is used. These crystals require lower half-wave voltages than traditionally used crystals like KDP. The KDP crystal requires half-wave voltages of approximately 3 kV and is hydroscopic. Both $LiNbO_3$ and $LiTaO_3$ are trigonal, 3m-symmetry, non-hydroscopic-class crystals that require half-wave voltages between 500 and 900 volts, resulting in power consumptions between 0.5 and 2.5 watts. Appendix A describes specific calculations and theory pertinent to electro-optic modulation with $LiNbO_3$ and $LiTaO_3$ crystals.

A crystal of $KTiOPO_4$ (KTP) will be used to frequency double the laser. KTP is a fairly new crystal which exhibits a very high frequency-doubling efficiency at 1.06 μm. Furthermore, KTP is a non-hydroscopic crystal, has a high damage threshold, and is thermally stable with wide angular and thermal bandwidths when phase matched in a type-II configuration. These physical properties make KTP one of the best available materials for frequency doubling [2]. Conversion efficiencies between 30 and 45 percent can be achieved with KTP. Specific calculations and relevant theory for frequency doubling with KTP are included in Appendix B.

Equipment for the above design has been ordered and received. However, failures of the commercially procured laser resulting from a design flaw in that unit have necessitated the return of the laser to the manufacturer. Upon receipt of the repaired laser, the dual-cavity design will be reassembled and tested.

V. Conclusion

In conclusion, a method has been described for efficiently frequency doubling while cavity dumping a solid-state laser. Using this technique provides a means for PPM modulating an optical communications link for deep space exploration at data rates between 1 Mbit/sec and 80 Mbit/sec (this assumes nominal laser repetition rates of 126 kHz – 10 MHz with $M = 256$). Lower data rates, up to approximately 500 kbits/sec, however, can be achieved by Q-switching the laser. The region between 500 kbits/sec and 1 Mbit/sec is considered an unstable region [3]; however, it is believed that by using some techniques as described above, either Q-switching or cavity dumping may be used to achieve these data rates for optical communication.

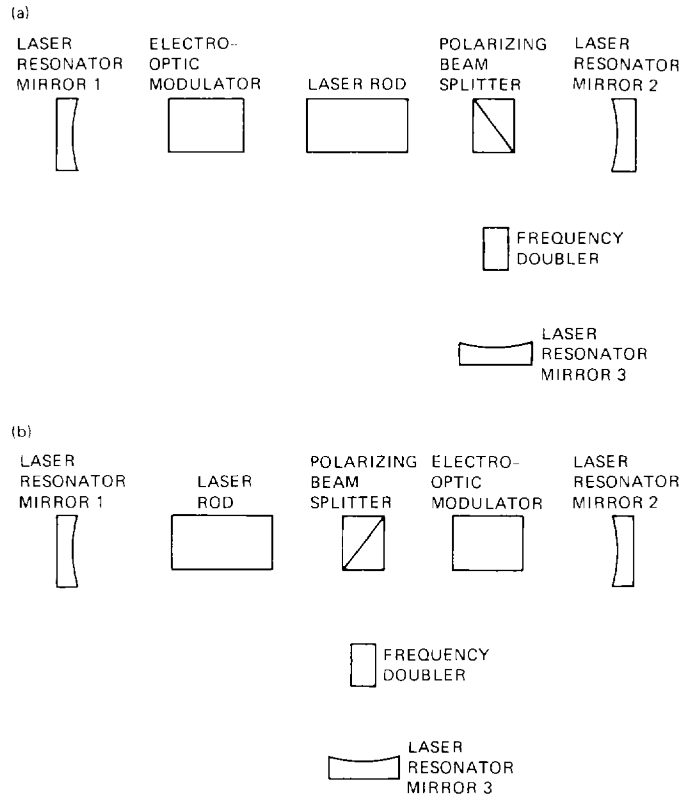

Fig. 1. Two overall optical schematics used for efficient frequency doubling while cavity dumping.

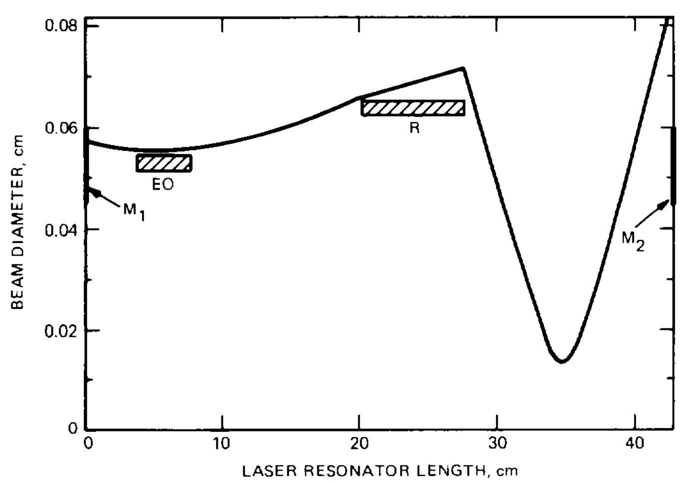

Fig. 2. A typical spatial spot size within the laser resonator where diameter of the beam is plotted as a function of the length of the laser cavity.

Appendix A
Electro-Optic Modulation with $LiNbO_3$ and $LiTaO_3$ Crystals

The following analysis describes electro-optic modulation using $LiNbO_3$ and $LiTaO_3$. Both $LiNbO_3$ and $LiTaO_3$ are trigonal, 3m-symmetry-class crystals. The electro-optic coefficients of a 3m crystal in tensor notation are of the form

$$\begin{pmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{pmatrix}$$

The specific values of the coefficients for $LiTaO_3$ and $LiNbO_3$ at 0.633 μm are as given for high-frequency operation [4]:

$$LiNbO_3 \begin{cases} r_{13} = 8.6 \times 10^{-12} \text{ m/V} \\ r_{22} = 3.4 \times 10^{-12} \text{ m/V} \\ r_{33} = 30.8 \times 10^{-12} \text{ m/V} \\ r_{51} = 28.0 \times 10^{-12} \text{ m/V} \end{cases}$$

$$LiTaO_3 \begin{cases} r_{13} = 7.5 \times 10^{-12} \text{ m/V} \\ r_{33} = 33.0 \times 10^{-12} \text{ m/V} \\ r_{22} = -1.0 \times 10^{-12} \text{ m/V} \\ r_{51} = 20.0 \times 10^{-12} \text{ m/V} \end{cases}$$

These values are dependent on the resonant frequencies of the crystal and will vary according to pulse rise time, crystal size, and frequency of operation. Given a specific crystal, these values must be calculated from the experimentally determined half-wave voltage. In the presence of an electric field $E(E_x, E_y, E_z)$ the equation of the index ellipsoid for the 3m crystal is as follows:

$$\left(\frac{1}{n_o^2} - r_{22} E_y + r_{13} E_z\right) x^2 + \left(\frac{1}{n_o^2} + r_{22} E_y + r_{13} E_z\right) y^2 + \left(\frac{1}{n_e^2} + r_{33} E_z\right) z^2 + 2\,(-r_{22} E_x)\, xy + 2\,(r_{51} E_y)\, yz + 2\,(r_{51} E_x)\, zx = 1 \tag{1}$$

where n_o denotes the ordinary and n_e denotes extraordinary indices of refraction.

Generally, in electro-optic modulation an electric field is only applied along one axis of the crystal, so this equation can be simplified to some extent. Since we are interested in transverse electro-optic modulation (as opposed to longitudinal electro-optic modulation) to rotate the polarization, we can eliminate cases where the axis of propagation is parallel to the electric field. Since highly efficient systems are needed for deep space optical communications, maximum phase retardation with the minimum amount of applied voltage is desirable. By applying an E field parallel to the z-axis, maximum phase retardation results with light propagating parallel to the x- or y-axis. Phase retardation for the case of x-axis propagation is given in Eq. (2) [5].

$$\Gamma = \left(\frac{\pi \ell_x V_z}{\lambda_o d_z}\right)(n_e^3 r_{33} - n_o^3 r_{13}) \text{ rad} \tag{2}$$

However, when used in this orientation, the indices of refraction are strongly dependent on temperature [6]. By applying an E-field parallel to the x- or y-axis, the temperature dependence can be eliminated for light propagating parallel to the z-axis. Phase retardation for this case of propagation, specifically for E_x, is given in Eq. (3). This is typically the orientation used with 3m crystals.

$$\Gamma = \frac{2\pi \ell_z V_x n_o^3 r_{22}}{\lambda_o d_x} \text{ rad} \tag{3}$$

In order to quantitatively compare Eqs. (2) and (3) for crystals of interest, we solve for the half-wave voltage and substitute appropriate electro-optic coefficients. The half-wave voltage is defined as the voltage required to induce a phase retardation of π. Half-wave voltages for $LiNbO_3$ and $LiTaO_3$

are summarized below for the indicated orientations. The length of the crystal is ℓ and d is the crystal thickness.

	V	(E field x or y) propagation z	V	(E field z) propagation x or y
$LiNbO_3$	$\frac{d}{\ell}$	1.3×10^4	$\frac{d}{\ell}$	4706.5
$LiTaO_3$	$\frac{d}{\ell}$	5.0×10^4	$\frac{d}{\ell}$	4005.9

When applying a field parallel to the x- or y-axis and propagating light parallel to the z-axis, $LiNbO_3$ is the preferred material to obtain lower required voltages. Even lower voltages can be obtained, however, by propagating in the x- or y-direction with an electric field parallel to the z-axis for both $LiNbO_3$ and $LiTaO_3$. In this crystal orientation the indices of refraction are more dependent on temperature, and thermally induced birefringence becomes a problem. This effect can be eliminated for uniform temperature variations across the crystal by utilizing two crystals with optic axes rotated 90 degrees. However, any temperature-induced gradient will be uncorrected by this technique. Since temperature gradients can result from nonuniformities in the laser beam or the applied electric field, the advantages of reduced required voltages are offset by thermally induced birefringence[1] Furthermore, it is difficult to obtain good optical quality $LiTaO_3$ with a high damage threshold appropriate for intra-cavity modulation. Further investigation is planned to quantitatively determine thermal birefringent effects since required voltages are less in the crystal orientation with the E-field applied parallel to the x- or y-axes. If thermal effects can be tolerated and good optical quality can be obtained, using $LiTaO_3$ would further reduce the half-wave voltage.

[1]T. Noricky, private communication, Engineering Manager, Inrad Corp.

For a spacecraft optical communication link, the overall power consumption of the modulator is important. In order to calculate this, the modulator can be treated as a capacitor. The capacitance, C, may be written as

$$C = \bar{\epsilon}\,\epsilon_o \frac{A}{d}$$

where A = electrode area, d = modulator thickness, ϵ_o = the free space permittivity constant, 8.85 pf/m, $\bar{\epsilon}$ = the dielectric constant. For $LiNbO_3$, $\bar{\epsilon} = 78$.[2] The resistance of the modulator is very small and can be neglected. However, the load resistance due to capacitance must be accounted for. Using well-known equations, the overall power consumption can be calculated

$$R_c = \frac{1}{(2\pi\omega C)} \qquad P = \frac{V^2}{R_c}$$

For a $LiNbO_3$ modulator of dimensions $30 \times 2 \times 2$ mm ($\ell \times d \times d$), C = 20.7 pf. Using a pulse width of 20 nsec (ω = 50 MHz), R_c = 153.8 ohms. For a quarter-wave voltage of V = 433.3 volts, peak power consumption is 1.2 kW. Assuming an average modulation rate of 100 kHz and a pulse width as given above, average power consumption is 2.4 watts.

[2]Ibid.

Appendix B
Frequency Doubling With KTP Crystals

The following analysis describes frequency doubling with $KTiOPO_4$ (KTP). KTP is a biaxial orthorhombic crystal of symmetry class mm2. The nonlinear optical tensor for the mm2 crystal is as follows:

$$\begin{pmatrix} 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 \end{pmatrix}$$

where

$$d_{15} = 5.40 \times 10^{-23} \text{ m/V}$$

$$d_{31} = 5.75 \times 10^{-23} \text{ m/V}$$

$$d_{32} = 4.43 \times 10^{-23} \text{ m/V}$$

$$d_{33} = 12.12 \times 10^{-23} \text{ m/V}$$

$$d_{24} = 6.73 \times 10^{-23} \text{ m/V}$$

for KTP (including ϵ_o) [2]. Multiplying this tensor by the E^2 column tensor leads to the following optical polarizations for KTP

$$P_x(2\omega) = 2d_{15}E_x(\omega)E_z(\omega)$$

$$P_y(2\omega) = 2d_{24}E_y(\omega)E_z(\omega)$$

$$P_z(2\omega) = d_{31}E_x^2(\omega) + d_{32}E_y^2(\omega) + d_{33}E_z^2(\omega)$$

By applying various axis rotations, these expressions can be simplified to an expression of the form

$$P = d_{\text{eff}}\, \mathcal{E}(\omega_1)\, \mathcal{E}(\omega_2)$$

where d_{eff} is an effective nonlinear coefficient obtained from the axis of rotation of the crystal and $\mathcal{E}(\omega_1)$ and $\mathcal{E}(\omega_2)$ are the electric fields applied at the respective frequencies.

Since KTP is a biaxial crystal, coordinate axis rotation is not a trivial problem and has been treated elsewhere [7]. Upon attaining the form of the above equation, Yao and Fahlen [7] have determined d_{eff} to be of the following form:

$$d_{\text{eff}} \approx 0.974\, d_{24} = 17.7 \times 10^{-9} \text{ e.s.u.}$$

$$= 6.51 \times 10^{-23} \text{ m/V}$$

(MKS, where ϵ_o is included in the coefficient)

There is some variance in the literature as to the experimental agreement with this value. Experimental values of d_{eff} range between 16.8×10^{-23} m/V [8] and 1.5×10^{-23} m/V [9]. These discrepancies from the theoretical d_{eff} values are most likely due to varying methods of crystal growth, material impurities, and phase matching techniques.

Knowing d_{eff}, the power conversion efficiency can be calculated with the following equation, assuming a depleted input source and complete phase matching [10, 11]

$$\eta = \frac{P^{(2\omega)}}{P^{(\omega)}} = \tanh^2\left(\frac{1}{2} K A(0) z\right)$$

where

$$K = d_{\text{eff}} \sqrt{\frac{\mu_o\, \omega_1^2\, \omega_2}{\epsilon_o\, n_1^2\, n_2}} \qquad \text{for } 2\,\omega_1 = \omega_2$$

and $A_1(0)$ can be derived from the following:

$$I = \frac{P}{A'} = \frac{1}{2}\sqrt{\frac{\epsilon_o}{\mu_o}}\, \omega\, |A|^2$$

where

$$A = \sqrt{\frac{n}{\omega}}\, E$$

and ω_1, ω_2, n_1, and n_2 are the frequencies and indices of refraction at the fundamental and second harmonic, respectively. The length of the crystal is Z, I is the incident intensity, P is the incident power, and A' is the area of the incident beam.

Since the power conversion efficiency is directly proportional to the length of the crystal and the intensity within the crystal, trade-offs result. As the beam is focused tighter, the beam diverges faster, resulting in less efficient frequency conversion at the entrance and exit faces of the crystal. The confocal parameter [10], z_o, gives guidance as to a reasonable crystal length

$$z_o = \pi \omega_o^2 \frac{n}{\lambda}$$

where ω_o = beam waist radius, n = index of refraction, and λ = the fundamental wavelength. As long as $\ell < 2 z_o$, acceptable conversion efficiency occurs. Therefore, the beam radius must be greater than

$$\omega_o > \sqrt{\frac{\lambda \ell}{(2\pi n)}}$$

Staying within this criterion, frequency-doubling efficiencies between 30 and 45 percent can be achieved. See [11] for a more detailed analysis of frequency doubling.

References

[1] W. Koechner, *Solid State Laser Engineering*, New York: Springer-Verlag, pp. 444–446, 1976.

[2] Y. S. Liu, L. Drafall, D. Dentz, and R. Belt, "Nonlinear Optical Phase-Matching Properties of $KTiOPO_4$," *G.E. Technical Information Series Report*, 82CRD016, February 1982.

[3] D. Maydan and R. B. Chesler, "Q-Switching and Cavity Dumping of Nd:YAG Lasers," *Journal of Applied Physics*, vol. 43, no. 3, pp. 1031–1034, March 1, 1971.

[4] A. Yariv and P. Yeh, *Optical Waves in Crystals*, New York: Wiley, pp. 220–270, 1984.

[5] P. V. Lenzo, E. G. Spencer, and K. Nassau, "Electro-Optic Coefficients in Single-Domain Ferroelectric Lithium Niobate," *Journal of the Optical Society of America*, vol. 56, no. 5, pp. 633–635, May 1966.

[6] J. D. Zook, D. Chen, and G. N. Otto, "Temperature Dependence and Model of the Electro-Optic Effect in $LiNbO_3$," *Applied Physics Letters*, vol. 11, no. 5, pp. 159–161, September 1967.

[7] J. Q. Yao and T. S. Fahlen, "Calculations of Optimum Phase Match Parameters for the Biaxial Crystal $KTiOPO_4$," *Journal of Applied Physics*, 55 (1), pp. 65–68, January 1, 1984.

[8] Y. S. Liu, D. Dentz, and R. Belt, "High-Average-Power Intracavity Second-Harmonic Generation Using $KTiOPO_4$ in an Acousto-Optically Q-Switched Nd:YAG Laser Oscillator at 5 kHz," *Optics Letters*, vol. 9, no. 3, pp. 76–78, March 1984.

[9] T. A. Driscoll, H. J. Hoffman, R. E. Stone, and P. E. Perkins, "Efficient Second-Harmonic Generation in KTP Crystals," *Journal of Optical Society of America B*, vol. 3, no. 5, pp. 683–686, May 1986.

[10] A. Yariv, *Quantum Electronics*, New York: Wiley, pp. 421–436, 1976.

[11] D. L. Robinson and R. L. Shelton, "Frequency Doubling Conversion Efficiencies for Deep Space Optical Communications," *TDA Progress Report 42-91*, Jet Propulsion Laboratory, Pasadena, Calif., pp. 112–123, July–September 1987.