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A Proposed "Twisted-Mode" Technique for Obtaining Single-Axial-Mode Oscillation in a Ruby Laser

by
A. E. Siegman

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Technical Report No. 0592-1

Prepared under
Signal Corps Contract DA 36(039) SC-90839

ELECTRON DEVICES LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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ABSTRACT

A proposed technique for obtaining oscillation in a single axial mode in a ruby laser is described and analyzed. The technique involves the use of a quarter-wave plate inside each laser mirror, together with a 0° ruby rod. The principal axes of the quarter-wave plates are rotated by 45° with respect to each other. The axial modes in this system have the form of twisted ribbons, with axially uniform transverse E field density, $E_x^2 + E_y^2 = \text{constant}$. It is believed that this will lead to axially uniform ruby saturation, and hence oscillation in a single axial mode. The general case of arbitrary wave plates at arbitrary angles has also been analysed, and the resulting mode forms and mode spectra are presented.

This report is an advance portion of the Final Report On Contract DA 36(039) SC-90839, covering one completed portion of the work under this contract.

NOTE ADDED IN PROOF

Since this report was completed, it has been discovered that essentially the same mode control scheme has also been proposed by V. Evtuhov, Hughes Research Laboratories, Malibu, California (unpublished reports) and also by J. M. Burch, National Physical Laboratory, Teddington, England (briefly mentioned by him in "Design of Resonators," in Quantum Electronics III, ed. by P. Grivet and N. Bloembergen, Columbia University Press, 1964, vol. 2, p. 1201).

CONTENTS

ILLUSTRATIONS

A PROPOSED "TWISTED-MODE" TECHNIQUE FOR OBTAINING SINGLE-AXIAL-MODE OSCILLATION IN A RUBY LASER*

I. INTRODUCTION

Ruby lasers generally oscillate simultaneously in several axial modes,[1] even though the atomic transition involved in the laser action is homogeneously broadened, and should permit only single-mode oscillation. Oscillation in multiple axial modes is generally undesirable from the viewpoint of potential laser applications.

According to the explanation of Tang, Statz, and deMars,[2] simultaneous axial mode oscillations can occur because different axial modes have different longitudinal standing-wave patterns and energy distributions, and also because different modes have null points at different locations along the ruby axis, so that different axial modes in essence make use of different regions of the ruby rod. Figure 1 shows the standing wave pattern and the resulting saturation in the rod, according to these authors.

As one consequence of this explanation, a prescription for achieving single-axial-mode operation in ruby is believed to be the use of a mode pattern which produces spatially uniform energy density and saturation throughout the ruby volume (no nodes along the axis). Tang, Statz, and deMars,[2] and also Kulevsky, Pashinin, and Prokhorov,[3] have proposed, for example, a running wave mode in a ring laser to achieve this condition; and Tang, Statz, and deMars have shown experimentally that this works as proposed.

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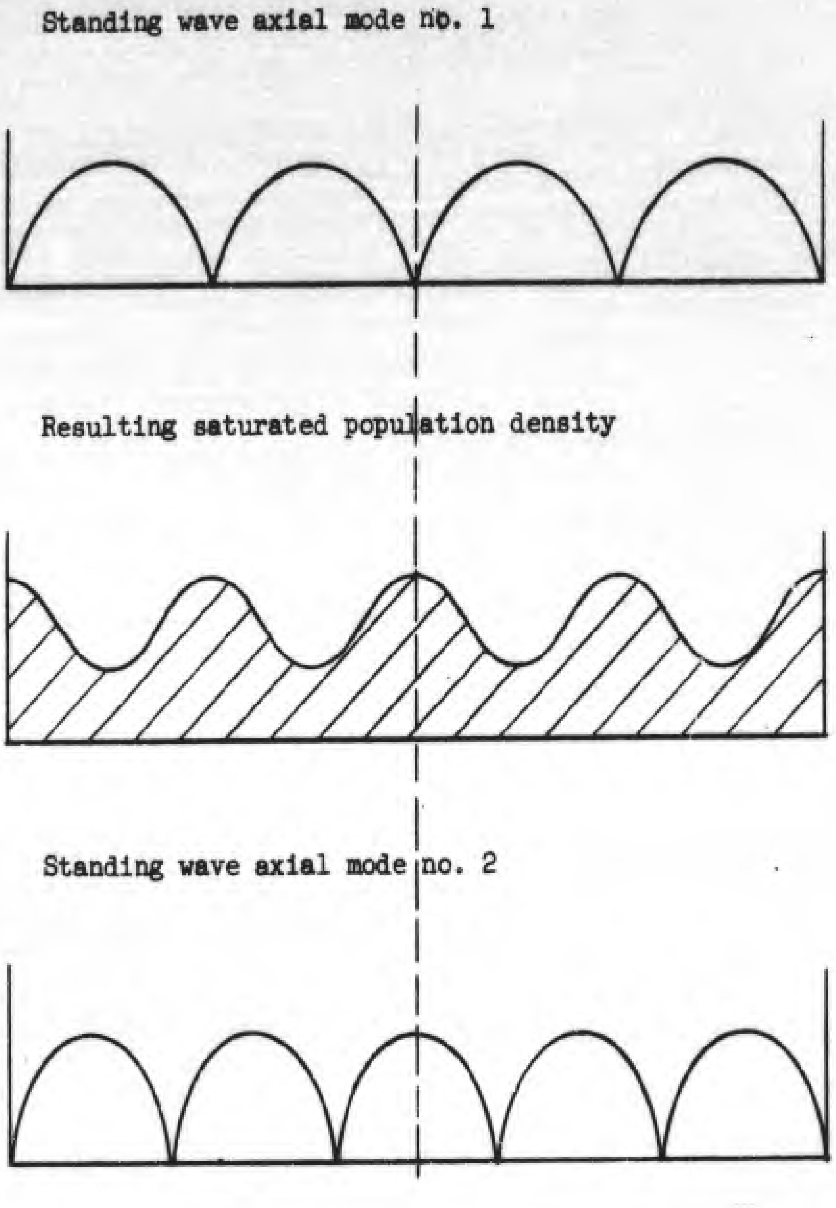
[*] This Technical Report is an expanded version of a Letter with the same title which has been submitted for publication in Applied Optics.



Standing wave axial mode no. 1

Resulting saturated population density

Standing wave axial mode no. 2

FIG. 1--A sketch adapted from reference 2 showing how one oscillating standing-wave mode leads to axiallly non-uniform ruby saturation, with maximum saturation at the standing wave peaks. A second standing-wave can then have some of its peaks in regions which are totally unsaturated by the first standing-wave.

We outline in this note a new method for achieving a standing wave mode with no nulls and with an axially uniform energy density in a laser cavity. The axial modes of an ordinary laser cavity really consist of two sets having orthogonal linear polarizations. This is usually not of interest in ruby, since only one set can oscillate due to the selection rules for the atomic transition. However, these polarizations can be interlocked and axially uniform energy density obtained by placing a birefringent element, specifically a quarter-wave plate, at each end of the laser cavity between the rod end and the mirror. If the rod is an accurately aligned 0° ruby rod, this will cause axially uniform saturation, and it is believed that the axially uniform saturation will in turn cause the rod to oscillate in a single axial mode only.

II. DESCRIPTION AND PROPERTIES OF THE TWISTED-MODE CONFIGURATION

Figure 2 shows the physical configuration envisioned. The 0° ruby rod (c-axis along the rod axis) will exhibit no birefringence if its alignment is sufficiently good and its quality is sufficiently high; and the laser transition will be equally stimulated by any transverse polarization of the optical electrical field. The rod axis is the z axis. While we have analyzed the general case of arbitrary wave plates with arbitrary rotation (see the Appendix), for the optimum arrangement the end sections should be birefringent quarter-wave plates, which may conveniently be made of sapphire; and the principal axes x',y' and x'',y'' of these birefringent sections should be rotated by 45° with respect to each other, as shown.

Among the important properties of this configuration are the following:

1. The normal modes (axial modes) of the structure may be viewed as consisting of either RH or LH circularly polarized waves traveling right and left in the center section. Consider, say, a RH circularly polarized wave traveling to the right. This wave is reflected from the right end section retaining the RH sense of circular polarization, but

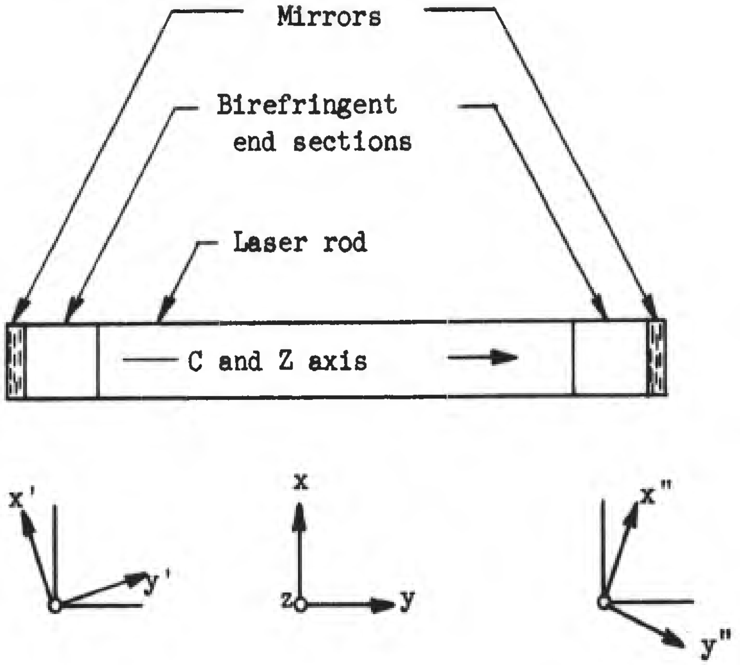


FIG. 2--The physical configuration proposed for the twisted-mode laser cavity.

going in the opposite direction.* (Two quarter-wave plates plus a mirror reflection equal a full-wave plate.) Thus, to an observer located outside the rod, the right-going and left-going RH waves appear to rotate oppositely, since one is approaching and one is receding from him. After reflecting in the same fashion off the left end section the wave still has its original RH polarization and can "catch its tail" to complete the mode. The same description would hold for an originally LH polarized wave.

2. Summing the right-going and the left-going RH or LH circularly polarized waves of a mode gives E_x and E_y standing waves which are spatially displaced with respect to each other by $\lambda/4$. That is, a rightgoing RH polarized wave can be written as

$$E_x = E_0 e^{-jkz}$$

$$E_y = jE_0 e^{-jkx} ,$$

and a left-going RH polarized wave can be written as

$$E_x = E_0 e^{jkz}$$

$$E_y = - jE_0 e^{jkz} .$$

Therefore, the combination of these waves is

$$E_x = E_0 \left(e^{-jkz} + e^{jkz}\right) = 2 \cos kz$$

$$E_y = jE_0 \left(e^{-jkz} - e^{jkz}\right) = 2 \sin z .$$

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[*] We consider that RH and LH should always be determined looking in the same sense with respect to the light's travel direction, e.g., always looking in the direction in which the light wave is travelling.

A similar result holds for LH polarized waves, by reversing the signs of the E_y terms. Therefore, in either case the total energy density $E_x^2 + E_y^2$ in a mode is uniform along the rod. The E-field mode pattern in the rod at an instant of peak E-field has the shape of a twisted ribbon with a spatial period of one optical wavelength, as shown in Fig. 3. Hence, we refer to this as a "twisted-mode" structure. The standing wave mode twists in opposite senses depending on whether it is made up from two RH or from two LH polarized running waves.

3. Let the total electrical length of the center section plus the mean electrical lengths of the two end sections (mean of the fast and slow axis phase shifts) be written as $\phi' = 2\pi L'/\lambda$. This defines a mean effective structure length L' for the rod plus the end sections. Then, the axial mode frequencies of this structure are given by (see the Appendix)

$$f_q = (q \pm \tfrac{1}{2}) \frac{c}{2L'} \quad ,$$

where q is any integer. The axial mode degeneracy is split symmetrically as indicated in Fig. 4. The (+) and (-) modes represent RH or LH circularly polarized waves, i.e., the alternate (+) and (-) modes have ribbon patterns twisting in opposite directions. To put this another way, a circularly polarized wave making a round trip must make, in effect, a slightly longer or shorter trip depending on whether it rotates with or against the relative rotations of the end sections. Therefore, the RH and LH modes are slightly separated in frequency.

4. The polarizations of the RH and LH twisted modes at the end faces (i.e., at the mirrors) are linear. The polarizations of the RH and LH modes are oriented at 90° to each other, and at 45° to the principal axes of the end sections. Therefore, the output of the laser will be linearly polarized, with a 90° rotation between RH and LH sets. A polarizing or dichroic element located just inside an end mirror could be used to completely eliminate either all of the RH or all of the LH set of modes.

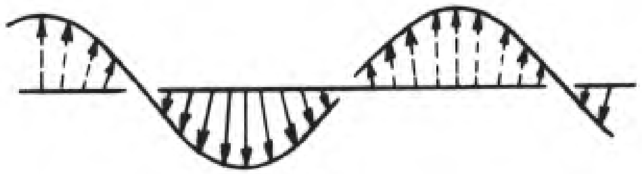

FIG. 3--A sketch of the instantaneous twisted-ribbon mode pattern in the center section of the optimum version of the laser cavity of Fig. 2. The entire ribbon contracts and expands at the resonant frequency, without any change in shape.

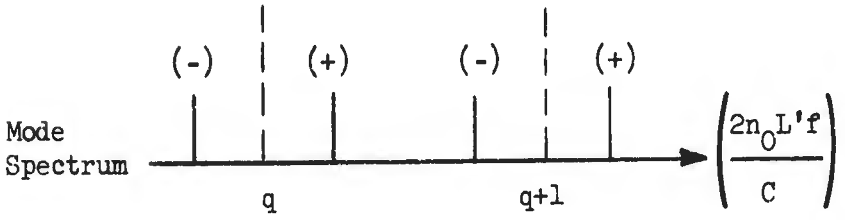

FIG. 4--The axial mode spectrum of the optimum form of twisted-mode laser. The (+) and (-) modes have opposite senses of twist.

III. DISCUSSION AND CONCLUSIONS

It is believed that such a twisted-mode ruby laser will oscillate in only a single such axial mode at once, although there may be a temporal jumping between RH and LH modes, which will result in 90° jumps of the output linear polarization. A complete analysis of the more general case of arbitrary-wave end sections with arbitrary rotations has also been carried out. This analysis, which is given in the Appendix, shows that the general case leads to various more complex mode patterns and splittings. The case presented above appears to be the optimum one in that it has uniform energy density, circular polarization, and the maximum possible mode splittings. Experimental tests of this concept are now being planned, using sapphire quarter-wave plates to be fabricated in this Laboratory plus a commercial 0° ruby rod. The axial modes oscillating will be examined with a Fabry-Perot interferometer and with microwave mode beating techniques [1] . These results will be reported when completed.

ACKNOWLEDGEMENTS

The author has benefited from several discussions with Professor S. E. Harris. The experimental work is being carried out by Duane Carlson.

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3. L. A. Kulevsky, P. P. Pashinin, and A. M. Prokhorov, "Travelling-Wave Ruby Laser," Quantum Electronics III, ed. by P. Grivet and N. Bloembergen, Columbia University Press, New York, 1964; p. 1065 in Vol. 2.

APPENDIX

DETAILED ANALYSIS OF THE GENERAL TWISTED-MODE LASER

A.1. ANALYSIS

The analytical model for the general twisted-mode laser rod is shown in Fig. A.1. The electrical length of the main section is ϕ , and the added electrical lengths along the x' and y' axes in the birefringent end sections are ϕ_+ and ϕ_- , respectively (which means that the x' axis is the slow axis). We pick an x,y coordinate system in the main section oriented midway between the principal axes of the end sections, which are rotated with respect to each other by a total angle θ .

For a rigorous analysis we should include the reflections at the interfaces between the different sections due to index mismatches. However, for simplicity we will assume that the indices obey $n \approx n_+ \approx n_-$, and neglect reflections.

Consider a running wave $\underset{\sim}{E}$ starting at the left hand end of the main section of the rod and traveling to the right. This wave has components

$$\underset{\sim}{E} = \begin{bmatrix} E_x \\ \\ E_y \end{bmatrix} .$$

In traveling down to the end section, the wave is multiplied by the transformation matrix

$$e^{-j\phi} \underset{\sim}{I} ,$$

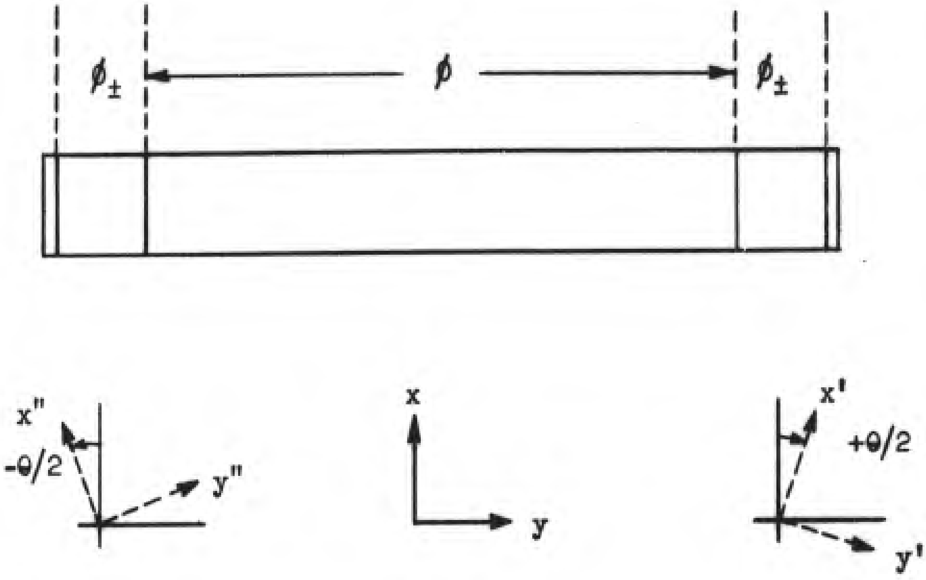

FIG. A.1--Analytical model for the twisted mode laser rod.

where $\underset{\sim}{I}$ is the identity matrix. We must then rotate coordinates into the primed system by using the rotation matrix

$$\underset{\sim}{R} = \begin{bmatrix} \cos \theta/2 & \sin \theta/2 \\ -\sin \theta/2 & \cos \theta/2 \end{bmatrix} .$$

Passage through the end section and back, with a sign-changing reflection off the end mirrors, multiplies waves in the rotated coordinate system by the differential phase shift matrix

$$-\underset{\sim}{D} = - \begin{bmatrix} e^{-j2\phi_+} & 0 \\ 0 & e^{-j2\phi_-} \end{bmatrix} .$$

Rotation from the primed system into the unprimed system, going to the left, is accomplished by the matrix

$$\underset{\sim}{R'} = \begin{bmatrix} \cos \theta/2 & -\sin \theta/2 \\ \sin \theta/2 & \cos \theta/2 \end{bmatrix} .$$

Transit to the left end of the main section requires another phase shift

$$e^{-j\phi} \underset{\sim}{I} .$$

Rotation into the double-primed system of the left end section is accomplished by

$$\underset{\sim}{R}' = \begin{bmatrix} \cos \theta/2 & -\sin \theta/2 \\ \sin \theta/2 & \cos \theta/2 \end{bmatrix} .$$

The differential phase and reflection throgh that end section give

$$- \underset{\sim}{D} = - \begin{bmatrix} e^{-j2\phi_+} & 0 \\ 0 & e^{-j2\phi_-} \end{bmatrix} .$$

Finally, rotation back into unprimed coordinates is by

$$\underset{\sim}{R} = \begin{bmatrix} \cos \theta/2 & \sin \theta/2 \\ -\sin \theta/2 & \cos \theta/2 \end{bmatrix} ,$$

and we are back at the starting place.

The condition for resonance is, then, that this wave match up with itself in a round trip, as expressed by the eigenvalue equation

$$e^{-j2\phi} [\underset{\sim}{R}\,\underset{\sim}{D}\,\underset{\sim}{R}'\,\underset{\sim}{R}'\,\underset{\sim}{D}\,\underset{\sim}{R}]\,\underset{\sim}{E} = e^{-jq2\pi}\,\underset{\sim}{E} ,$$

where q is any integer. To evaluate this, we can first show by matrix multiplication that

$$\underset{\sim}{R}'\,\underset{\sim}{D}\,\underset{\sim}{R} = e^{-j(\phi_+ + \phi_-)} \begin{bmatrix} \cos\Delta\phi - j\cos\theta\sin\Delta\phi & -j\sin\theta\sin\Delta\phi \\ -j\sin\theta\sin\Delta\phi & \cos\Delta\phi + j\cos\theta\sin\Delta\phi \end{bmatrix} ,$$

where $\Delta\phi \equiv \phi_+ - \phi_-$ is the retardation of the birefringent sections; and also that

$$\underset{\sim}{R}\,\underset{\sim}{D}\,\underset{\sim}{R}' = e^{-j(\phi_+ + \phi_-)} \begin{bmatrix} \cos\Delta\phi - j\cos\theta\sin\Delta\phi & j\sin\theta\sin\Delta\phi \\ j\sin\theta\sin\Delta\phi & \cos\Delta\phi + j\cos\theta\sin\Delta\phi \end{bmatrix}$$

is true. Multiplying these together, and using $\phi' \equiv \phi + \phi_+ + \phi_-$ for the total mean phase shift along the rod, leads to the result

$$\begin{bmatrix} \sin^2\theta + \cos^2\theta\cos 2\Delta\phi - j\cos\theta\sin 2\Delta\phi & -\sin\theta\cos\theta\,(1 - \cos 2\Delta\phi) \\ \sin\theta\cos\theta\,(1 - \cos 2\Delta\phi) & \sin^2\theta + \cos^2\theta\cos 2\Delta\phi + j\cos\theta\sin 2\Delta\phi \end{bmatrix} = e^{j(2\phi' - q2\pi)}\,\underset{\sim}{I} .$$

If we let $\gamma \equiv e^{j(2\phi' - q2\pi)}$ be the eigenvalue and calculate the secular determinant for the system, the secular equation becomes, after some algebra,

$$\gamma^2 - 2\alpha\gamma + 1 = 0 \quad ,$$

where α can be written in either of these two forms

$$\begin{aligned} \alpha &\equiv \sin^2\theta + \cos^2\theta \cos 2\Delta\phi \\ &\equiv 1 - 2\cos^2\theta \sin^2 \Delta\phi \end{aligned}$$

Therefore, the eigenvalues of the system are given by

$$\gamma = e^{j(2\phi' - q2\pi)} = \alpha \pm j\sqrt{1 - \alpha^2} \quad ,$$

or the allowed values of ϕ' are given by

$$\phi'_q = \pm \frac{1}{2} \cos^{-1}\alpha + q\pi \quad , \quad q = \text{integer} \quad .$$

Note that α is bounded, $-1 \leq \alpha \leq 1$, as required for this interpretation.

The quantity ϕ' is the mean electrical length along the rod including end sections. It can be written as

$$\phi' = \frac{2\pi f L'}{c} \quad ,$$

where L' is the effective length of the rod. We should also note that the retardation $\Delta\phi \equiv \phi_+ - \phi_-$, which is contained in α , has some frequency dependence. This dependence is very slow, however; we will neglect it for exactly the same reasons that the frequency dependence of, say, a quarter-wave or half-wave plate is usually neglected in considering a limited frequency range. Therefore, the resonant frequencies of the cavity are given by

$$f_q = \frac{c}{2\pi L'} \phi'_q$$

$$= \frac{c}{2L'} \left[q \pm \frac{\cos^{-1}\alpha}{2\pi} \right] \quad .$$

Different values of q (which is normally a very large integer) represent different axial modes of the resonantor.

We also wish to know the fields (i.e., the polarizations) associated with the normal modes. From the eigenmatrix equation we can obtain the relationship

$$[\sin^2\theta + \cos^2\theta \cos 2\Delta\phi - \gamma - j \cos\theta \sin 2\Delta\phi]\, E_x$$

$$- \; [\sin\theta \cos\theta\, (1 - \cos 2\Delta\phi)]\, E_y = 0 \quad .$$

Putting in the eigenvalues for γ then yields

$$\frac{E_y}{E_x} = -j \, \frac{\cos\theta \sin 2\Delta\phi \pm \sqrt{1 - \alpha^2}}{\sin\theta \cos\theta\, (1 - \cos 2\Delta\phi)} = -j\beta \quad ,$$

which yields the important result that E_y and E_x are in quadrature. These fields are the amplitudes of the wave traveling to the right in the rod, i.e., in the main portion of the rod. We then have

$$\underset{\sim}{E}^{+} = e^{j(\omega t-kz)} \begin{bmatrix} E_0 \\ -j\beta E_0 \end{bmatrix} ,$$

where β is the relative amplitude factor defined by the previous equation. It is useful to note that after some algebra β can be reduced to the form

$$\beta = \frac{\cos \Delta\phi \pm \sqrt{1 - \cos^2\theta \sin^2 \Delta\phi}}{\sin \theta \sin \Delta\phi} .$$

The wave $\underset{\sim}{E}^{-}$ traveling to the left in the rod is the right-going wave $\underset{\sim}{E}^{+}$ after it has been reflected off the end mirror through the end section, as expressed by

$$\underset{\sim}{E}^{-} = e^{j(\omega t+kz)} [\underset{\sim}{R}' \underset{\sim}{D} \underset{\sim}{R}] \begin{bmatrix} E_0 \\ -j\beta E_0 \end{bmatrix} .$$

The minus sign and the constant phase factor $(\phi_+ + \phi_-)$ can be eliminated if desired by absorbing them into the choice of the origin of z. Direct evaluation of this expression leads, again after some algebra, to

$$\underset{\sim}{E}' = \left[\pm\sqrt{1 - \cos^2\theta \sin^2 \Delta\phi} + j \cos \theta \sin \Delta\phi \right] e^{j(\omega t+kz)} e^{-j(\phi_+ + \phi_-)} \begin{bmatrix} E_0 \\ +j\beta E_0 \end{bmatrix}$$

Note that the factor in front has magnitude of unity.

Examination of these results reveals that $\underset{\sim}{E}^{-}$ for an eigenmode has exactly the same elliptical polarization as does $\underset{\sim}{E}^{+}$, the ellipticity of the polarization being determined by β . The E_y component changes sign because the x,y coordinate system has opposite "handedness" for waves traveling right or left. The polarizations associated with the two allowed values of β are the "eigen-polarizations" of the overall system.

A crucial point is that the total field amplitudes E_x and E_y including right and left components have the z dependences

$$E_x(z) \propto E_0 \cos kz$$

and

$$E_y(x) \propto \beta E_0 \sin kz \quad .$$

Hence, if $\beta \sim 1$, the total field intensity $|E_x^2| + |E_y|^2$ is uniform along the rod. Therefore, if the x and y transition probabilities are not too different, the inverted population in a laser rod should saturate uniformly along the length of the rod. This is the condition which is believed to lead to single axial mode operation.

A.2. VARIOUS SPECIAL CASES

We now check all of the preceeding analysis by considering various special cases.

1. <u>No rotation, $\theta = 0$, $\Delta\phi$ finite</u>: The x' and x'' , and y' and y'' , axes are aligned with each other in this situation. It is then physically obvious that the eigenmodes will be linearly polarized along $x \equiv x' \equiv x''$ or $y \equiv y' \equiv y''$, with different resonant frequencies

for each. The analysis gives:

$$\alpha = \cos 2\Delta\phi$$

$$\phi'_q = q\pi \pm \Delta\phi$$

$$f'_q = \frac{c}{2L'} \quad q \pm \frac{\Delta\phi}{\pi}$$

$$\beta = \infty \text{ or } 0 \quad .$$

The top sign is polarized along y, which is the electrically shorter axis in the end sections. Hence, the resonant frequencies are increased by an amount corresponding to the extra electrical length $\Delta\phi$. The bottom clearly represents linear polarization along x, the electrically longer polarization in the end sections, with consequently lowered resonant frequencies.

2. <u>No birefringence, $\Delta\phi = 0$, θ arbitrary</u>: In this case, the analysis gives

$$\alpha = 1$$

$$\phi'_q = q\pi$$

$$F_q = q\,\frac{c}{2L'}$$

$$\beta = \text{indeterminate} \quad .$$

Because there is complete rotational symmetry, any orthogonal pair of polarizations may be chosen as eigen-polarizations; the two polarizations are completely degenerate, in agreement with physical intuition. Hence, β is entirely indeterminate.

3. $\theta = \pi/2$, $\Delta\phi$ finite: In this case the x' and y'' axes, and hence also the y' and x'' axes, are aligned. One expects the eigenpolarizations to be linear along these axes, since such polarizations are obviously preserved upon reflection. Also, these two polarizations should be degenerate, since each axis has the same electrical length, with the added length in one end section being cancelled at the opposite end. The analysis gives:

$$\alpha = 1$$

$$\phi'_q = q\pi$$

$$f'_q = q\,\frac{c}{2L}$$

$$\beta = \frac{\cos\Delta\phi \pm 1}{\sin\Delta\phi} \quad .$$

The modes are degenerate. The rather odd value of β presumably results because linear combinations of x' or y' linear polarizations are also eigenmodes due to the existence of degeneracy; but the x' and y' polarizations are displaced along the z direction with respect to each other due to the birefringence in the end sections.

A.3. THE OPTIMUM TWISTED-MODE CASE

In the general case we are seeking a value of β on the order of unity, and a maximum degeneracy in frequency. Fortunately, this is readily achieved as follows. We note that the maximum frequency spacing between modes is achieved if

$$f_q = \frac{c}{2L'}\,[q \pm 1/4] \quad ,$$

which requires that

$$\cos^{-1}\alpha = \pi/2 \quad ,$$

and hence

$$\alpha = 0 \quad .$$

This can be accomplished generally if

$$\cos^2\theta \sin^2 \Delta\phi = 1/2 \quad ,$$

which gives for β

$$\beta = \frac{\cos \Delta\phi \pm \quad 1/2}{\sin \theta \sin \Delta\phi} \quad .$$

However, we know that both $\theta = 0$ and $\theta = \pi/2$ are special cases to be avoided, and so we chose $\theta = \pi/4$ as the midpoint of these extremes. This immediately gives the desired results:

$$\cos^2\theta = \sin^2\theta = \frac{1}{2} \quad , \quad \theta = \pi/4$$

$$\sin^2 \Delta\phi = 1 \quad , \quad \cos^2 \Delta\phi = 0$$

$$\beta = \pm 1 \quad .$$

Note that the total retardation in this case in passing through the end section and back is equal to

$$2\Delta\phi = \pi \quad .$$

It is evident that with this retardation an incident circularly polarized wave $\underset{\sim}{E}^{+} \propto (1\ ,\ \pm j)$ will be reflected as a departing circularly polarized wave having the same sense of circular polarization $\underset{\sim}{E}^{-} \propto (1\ ,\ \mp j)$ with respect to its reversed direction of travel.

Consider the optimum case. We then have

$$\theta = \pi/4 \quad , \quad \Delta\phi = \pi/2$$

$$f_q = \frac{c}{2L'}\ [q \pm 1/4]$$

$$\beta = \pm 1 \quad .$$

The wave coming into the end section is circularly polarized and given at the end section interface (denoted by $z = 0$) by

$$\underset{\sim}{E}_0^{+} = E_0 \begin{bmatrix} 1 \\ \mp j \end{bmatrix} \quad .$$

The wave emerging from the end section is also circularly polarized and given by

$$\underset{\sim}{E}_0^{-} = \frac{1}{2}\,[\pm 1 + j]\,E_0 \begin{bmatrix} 1 \\ \pm j \end{bmatrix} e^{-j(\phi_+ + \phi_-)}$$

$$= j\,\frac{1}{2}\,[1 \mp j]\,E_0 \begin{bmatrix} 1 \\ \pm j \end{bmatrix} e^{-j(\phi_+ + \phi_-)}$$

$$= e^{j\frac{\pi}{2}}\ e^{j\mp\pi/4}\ E_0 \begin{bmatrix} 1 \\ \pm j \end{bmatrix} e^{j(\phi_+ + \phi)} \quad .$$

Let us try to trace these waves back into the end section, to see if purely linear polarization emerges anywhere.

The forward wave $\underset{\sim}{E}_0^{+}$ transforms to x',y' components just inside the end section interface given by

$$\underset{\sim}{E}_0^{+'} = \begin{bmatrix} \cos\frac{\theta}{2} & \sin\frac{\theta}{2} \\ -\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix} \underset{\sim}{E}_0^{+} ,$$

and these then propagate into the end section according to the matrix

$$\underset{\sim}{D} = \begin{bmatrix} e^{-j\phi_+} & 0 \\ 0 & e^{-j\phi_-} \end{bmatrix} .$$

Note that for the optimum value $\theta = \pi/4$ we have

$$\cos\theta/2 = \cos\pi/8 = \frac{1}{2}\sqrt{2 - \sqrt{2}}$$

$$\sin\theta/2 = \sin\pi/8 = \frac{1}{2}\sqrt{2 + \sqrt{2}} .$$

The reflected wave $\underset{\sim}{E}_0^{-}$ is obtained from an x',y' wave $\underset{\sim}{E}_0^{-'}$ just inside the end section interface by

$$\underset{\sim}{E}_0^{-} = \begin{bmatrix} \cos\theta/2 & -\sin\theta/2 \\ \sin\theta/2 & \cos\theta/2 \end{bmatrix} \underset{\sim}{E}_0^{-'} ,$$

and hence the converse is

$$\underline{E}_0^{-'} = \begin{bmatrix} \cos \theta/2 & \sin \theta/2 \\ -\sin \theta/2 & \cos \theta/2 \end{bmatrix} \underline{E}_0^{-} \quad .$$

This wave transforms back into the end section according to the matrix

$$\underline{D}^* = \begin{bmatrix} e^{j\phi_+} & 0 \\ 0 & e^{j\phi_-} \end{bmatrix} \quad .$$

Therefore, the total wave intensity inside the end section is given by

$$\underline{E}' = \underline{D}\,\underline{E}_0^{+'} + \underline{D}^*\,\underline{E}_0^{-'}$$

$$= \begin{bmatrix} e^{-j\phi_+} & 0 \\ 0 & e^{-j\phi_-} \end{bmatrix} \frac{1}{2} \begin{bmatrix} \sqrt{2-\sqrt{2}} & \sqrt{2+\sqrt{2}} \\ -\sqrt{2+\sqrt{2}} & \sqrt{2-\sqrt{2}} \end{bmatrix} \begin{bmatrix} 1 \\ \mp j \end{bmatrix} E_0$$

$$+ \begin{bmatrix} e^{j\phi_+} & 0 \\ 0 & e^{j\phi_-} \end{bmatrix} \frac{1}{2} \begin{bmatrix} \sqrt{2-\sqrt{2}} & \sqrt{2+\sqrt{2}} \\ -\sqrt{2+\sqrt{2}} & \sqrt{2-\sqrt{2}} \end{bmatrix} \begin{bmatrix} 1 \\ \pm j \end{bmatrix} e^{j(\frac{\pi}{2}\pm\frac{\pi}{4})}\, e^{-j(\phi_+ + \phi_-)}\, E_0$$

$$= e^{-j\phi_+}\, E_0/2 \begin{bmatrix} \left\{\sqrt{2-\sqrt{2}} \mp j\sqrt{2+\sqrt{2}} - \frac{1\mp j}{2}\sqrt{2-\sqrt{2}} \mp j\,\frac{1\mp j}{2}\sqrt{2+\sqrt{2}}\right. \\ \pm\left\{\sqrt{2-\sqrt{2}} \mp j\sqrt{2+\sqrt{2}} - \frac{1\mp j}{2}\sqrt{2-\sqrt{2}} \mp j\,\frac{1\mp j}{2}\sqrt{2+\sqrt{2}}\right. \end{bmatrix},$$

which is linear polarization, as expected.

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