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PHASE CONJUGATION IN OPTICAL FIBER
VIA STIMULATED BRILLOUIN SCATTERING WITH
FEEDBACK FROM A BARIUM TITANATE CRYSTAL

THESIS

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THESIS

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Preface

I would like to thank all those individuals who made the completion of this thesis possible. To begin, I would like to thank my advisor, Dr. Won Roh, without whose suggestions and insight this thesis would have been impossible. I would also like to thank Capt Jeffrey Druessel whose help saved me much time and effort getting started in the lab. Finally, I would like to thank my friends who remained friends after I had effectively disappeared while completing this thesis.

Patrick R. Emmert

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Abstract

The goal of this thesis was to obtain phase conjugation in multi-mode optical fiber via stimulated Brillouin scattering (SBS) with the aid of a barium titanate crystal which formed a phase conjugate cavity for the Stokes beam. SBS was demonstrated but the SBS threshold was unaffected by the presence of the $BaTiO_3$ crystal and no evidence for the presence of phase conjugation in the optical fiber was obtained.

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I. Introduction

As an optical beam propagates through the atmosphere it is degraded by atmospheric turbulence. The Air Force, and the scientific community in general, have many current and proposed applications where the transmitted or received optical beam is too degraded by atmospheric turbulence to be of use. An obvious example is astronomical observations where it is necessary to get above the atmosphere to obtain meaningful information. One technique for overcoming this atmospheric "seeing" problem is through the use of nonlinear optical phase conjugation, which removes the distortion of the optical wave through wave front reversal. This thesis investigates the generation of a phase conjugate wave through stimulated Brillouin scattering (SBS) in optical fiber with the aid of a phase conjugating crystal, in this case barium titanate ($BaTiO_3$).

1.1 Previous Experiments

The ability of stimulated Brillouin scattering to phase conjugate an incident beam was first demonstrated by Zel'dovich et. al. in 1972.[1] That experiment consisted of illuminating a glass light pipe placed in a cell of methane gas by a ruby laser. The laser light first passed through a glass plate etched with hydrofluoric acid to distort the beam, and the divergence of the resulting backscatter from the light pipe was then compared with the divergence of the incident laser beam. It was shown that the divergences were essentially identical which could only be the case if the SBS beam was the phase conjugate replica of the distorted beam. When the experiment was repeated with the light pipe replaced by a plane mirror the divergence of the backscattered light was significantly greater, as would be expected with a non-phase conjugating mirror.

Stimulated Brillouin scattering, as well as stimulated Raman scattering (SRS) have also been demonstrated in glass fibers. SBS was first achieved in fiber by Ippen and Stolen also in 1972.[2] That experiment consisted of illuminating a length of 3.8 μm diameter fiber by a 5355 Å xenon laser source. They were able to observe SBS at input powers of under 1W, and with long lengths of fiber, at powers as low as 40 mW.

Investigations of SBS in optical fiber have been ongoing at AFIT in recent years. In 1990 SBS was demonstrated in multimode optical fiber using a CW argon-ion laser source.[3] In the following year, the work was continued to observe phase conjugation by SBS through the use of an optical fiber ring laser.[4] Although that work was successful in lowering the threshold power required for SBS onset, no phase conjugation of the Stokes beam was detected. The present experiment has been an attempt to modify that previous study by the inclusion of a phase conjugating crystal, in this case barium titanate ($BaTiO_3$), to determine if feedback from the crystal would initiate phase conjugation in the SBS.

II. Theory

In this section, the concepts of phase conjugation, SBS in optical fiber and phase conjugation in $BaTiO_3$ crystal will be presented with the intention of illuminating those aspects of each that are relevant to the work at hand.

2.1 Phase Conjugation

Phase conjugation, at its most fundamental, deals with the conversion of a monochromatic optical field

$$E_1(r, t) = \mathrm{Re}[\psi(r)e^{i(\omega t-kz)}] \tag{1}$$

into a new field which is proportional to

$$E_2(r, t) = \mathrm{Re}[\psi^*(r)e^{i(\omega t+kz)}] \tag{2}$$

traveling in the opposite direction. This process is referred to as phase conjugation because E_2 is obtained from E_1 by replacing the spatial part of the envelope function, $\psi(r)e^{ikz}$, with its complex conjugate $\psi^*(r)e^{-ikz}$. The result of such a transformation can be illustrated by the following figure.

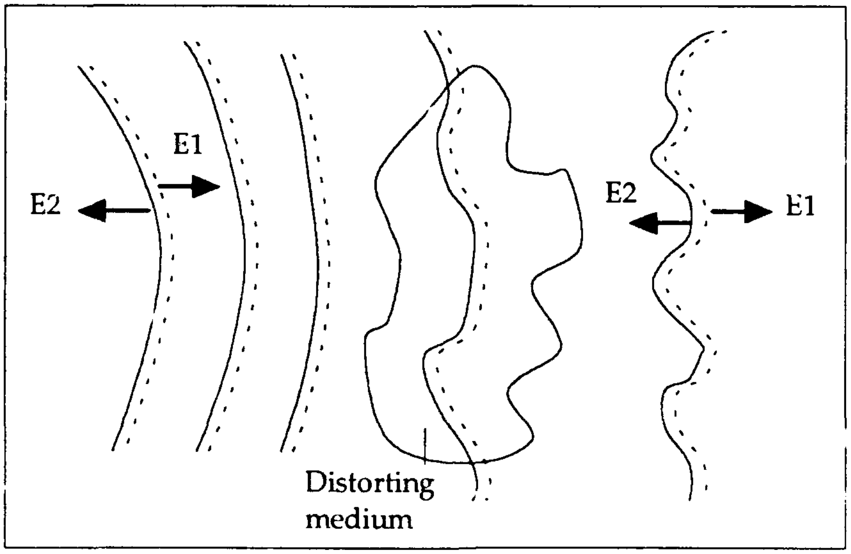

Figure 1. Phase Conjugation

If a monochromatic plane wave moving to the right, travels through a distorting, lossless dielectric medium such as the one shown above, it will be either advanced or retarded by the medium, destroying the planar nature of the wave. If this distorted wave is somehow phase conjugated, using processes that will be described, and reflected back through the medium it will emerge having regained its original planar quality. The proof of this distortion correction ability is demonstrated by plugging equations 1 and 2 into the wave equation, which is,

$$\nabla^2 E + \omega^2 \mu \varepsilon(\mathbf{r}) E = 0 \tag{3}$$

and taking the complex conjugate of the result. One obtains

$$\nabla^2 \psi_1^* + [\omega^2 \mu \varepsilon^*(\mathbf{r}) - k^2] \psi_1^* + 2ik\, [\partial \psi_1^* / \partial z] = 0 \tag{4}$$

and

$$\nabla^2\psi_2 + [\omega^2\mu\varepsilon(\mathbf{r}) - k^2]\psi_2 - 2ik\,[\partial \psi_2/\partial z] = 0 \tag{5}$$

In this case, where the medium has been specified as lossless, $\varepsilon(r)$ and $\varepsilon^*(r)$ are identical which means that the waves ψ_1^* and ψ_2 are solutions to the same equation. From this it follows that if they are equivalent to within a multiplicative constant at some point ($z = 0$), then due to the uniqueness theorem $\psi_1^*(x,y,z) = \psi_2(x,y,z)$ for all $x,y,z < 0$. Techniques for phase conjugation vary from the simple and inexpensive, to the intricate and costly. To phase conjugate a plane wave, all that is required is a flat mirror. In a similar manner, to phase conjugate a diverging spherical wave, requires reflecting it by a concave mirror whose center of curvature coincides with the point source of the spherical wave.[5] For real-life applications, however, phase conjugation (PC) is a much more complicated affair. Various techniques such as adaptive optics using deformable mirrors have led to some success but are very complicated. Nonlinear optics is another method that has been used to phase conjugate and holds the promise of providing a real-time phase conjugation ability with much less complexity and cost. The following sections will outline PC through degenerate four wave mixing in a photorefractive crystal and through SBS in optical fiber.

2.2 Phase Conjugation in $BaTiO_3$ Crystal

The photorefractive effect was first noticed in the late sixties in $LiNbO_3$ crystal when, during attempts at second harmonic generation, the efficiency became significantly poorer after a few laser shots. It was determined that the laser pulse caused a semi-permanent change in the refractive index of the crystal.[6] Phase conjugation in such crystals has been generated primarily through two processes. One of these is two-beam coupling, first demonstrated in 1985 by Chang and Hellwarth, where phase conjugation is generated by backscattering of the input beam by an index grating formed in the crystal.[7] The other, earlier method, demonstrated in 1982 by Feinberg employs a degenerate four-wave mixing approach.[8] This is the method that has been used in this thesis and will be explained below.

Phase conjugation in $BaTiO_3$, and similar crystals, depends upon the photorefractive effect. This effect, while complicated because of the uncertainty of the exact mechanism of charge migration, can be summarized in the following three steps;

1. Light liberates charge to migrate and separate in the crystal.
2. The separation of charge produces a strong electrostatic field.
3. This electrostatic field causes a change in the refractive index of the crystal by the linear electro-optic effect (Pockels Effect).[6]

The sources of charges for migration is thought to be traps formed by impurities or defects in the crystal. Under illumination, the charges move between trapping sites. The electro-optic effect, otherwise known as the Pockels effect, can only exist in those crystals that lack a center of symmetry, meaning they have no center point through which every atom in the crystal can be paired to an identical atom. Of the 20 crystal classes which lack this symmetry, all are piezoelectric.[7] The strength of the photorefractive effect, unlike other light-induced refractive index change mechanisms, is not dependent upon the absolute intensities of the incident beams but upon their intensity ratio.[6] This means that an optical beam of very low intensity can generate a large refractive index change, albeit over a longer time period than with a more intense beam.

The phase conjugation process used in this thesis has been called self-pumped four-wave mixing, and is self-pumped in the sense that the two customary writing beams normally required for four-wave mixing are generated by one incident beam within the crystal. These self-pumping beams are caused by Fresnel reflections off of the crystal faces, although reflections from mirrors outside of the crystal have also been demonstrated.[10] Such self-pumping beams are generally self starting, and self sustaining, requiring no input other than that of the incident laser beam. Looking at the geometry illustrated in Figure 2., one can see how the four beams interact within the crystal. The incident beam enters from the right and is polarized in the plane of the paper (extraordinary ray). This beam undergoes what is known as "fanning" which is caused by asymmetric self-defocusing in the plane formed by the C axis of the crystal and the input beam.[8] This preferential amplification of scattered light varies according to the modulation depth of the index grating,[11] which is in turn dependent upon the ratios of the two "writing" beams. The photorefractive grating corresponding to the phase conjugate fanning is much more efficient at transferring light from the incident beam during the initiation process, and thus it becomes the dominant grating.[10] The light curvature is also dependent upon the propagation angle of the entering beam. It has been demonstrated that at some angles extra beams do not form within the crystal in which case the phase conjugation process is simply backscatter by an index grating. At other angles the internal beams do form and then the phase conjugation process is four-wave mixing discussed here.

The fan collapses into at least two counter propagating beams which mix with the incident beam to generate the phase conjugate signal beam. This condition is shown in Figure 2b. The incident beam enters the crystal at an angle and is split off in the right interaction region into beam 2. This resulting beam is internally reflected twice near the edge of the crystal. After the second reflection, beam 2 becomes beam 3', and intersects beam 1, the incident beam, in

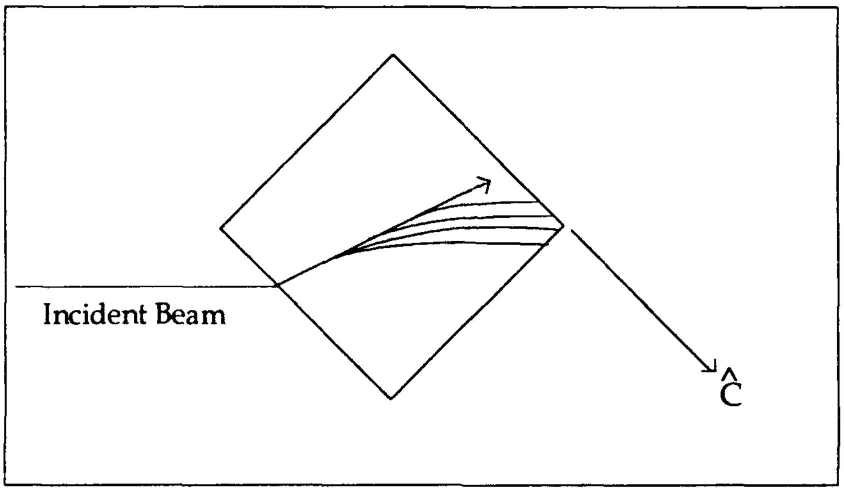

Figure 2a. Formation of "Fanning" Within $BaTiO_3$ Crystal

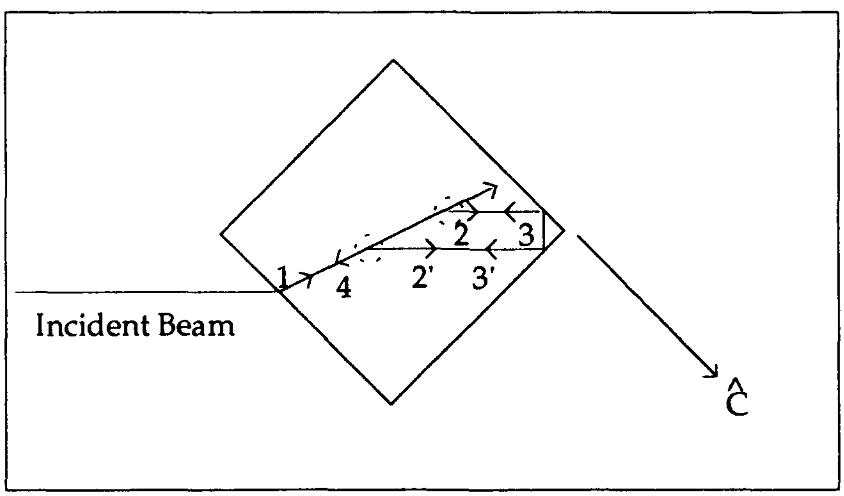

Figure 2b. Generation of Phase Conjugate Beam Through Degenerate Four-Wave Mixing

the left interaction region. Beam 2', having split from beam 1 in the same fashion as beam 2, travels around the loop in the opposite direction. Beams 1-3 generate the output beam, 4, in the right interaction region, while beams 1, 2' and 3' generate 4 in the left interaction region.[8] The two counter-propagating beams experiencing the internal corner cube reflections must be a mutual phase conjugate pair because the photorefractive gratings involved in the generation of beams 2 and 2', are reinforced by the two sets of writing beams. The two pairs of beams double the index modulation for the gratings, which effectively squares the enhancement to the two-wave mixing gain. This enhancement occurs only for those gratings that correspond to the mutual phase conjugated pair of pump beams.[10]

With eight beams coinciding in two interaction regions, the theory predicts that phase conjugation will begin when the product of the length of the effective interaction region and γ, the coupling constant per unit length, is greater than or equal to 2.34.[8] The coupling constant is a function of several variables, most essentially the angles (α_1 and α_2) of the two beams, 1 and 2', with the C axis of the crystal and with the effective Pockels coefficient, r_{eff}. The coupling constant is[12]

$$\gamma = E\, r_{eff}\, (\omega/2nc) / \cos[(\alpha_1 - \alpha_2)/2] \tag{6}$$

where in the absence of an applied or intrinsic field, the electric field is

$$E = kk_bT / q[1 + (k/k_o)^2] \tag{7}$$

$$k_o = [Nq^2 / (\varepsilon\varepsilon_o k_b T)]^{1/2} \tag{8}$$

$$r_{eff} = [n_o^4\, r_{13} \cos\alpha_1 \cos\alpha_2 + 2n_e^2\, n_o^2\, r_{42} \cos^2[(\alpha_1 - \alpha_2)/2] + n_e^4 r_{33} \sin\alpha_1 \sin\alpha_2] * \sin[(\alpha_1 - \alpha_2)/2] \tag{9}$$

In this case, k_bT is the thermal energy, k is the magnitude of the grating wave vector, ω is the optical frequency, n is the crystal index of refraction, r_{ij} are the Pockels coefficients of the crystal and $\varepsilon\varepsilon_o$ is the static dielectric constant in the direction of k. The point of this derivation is to illustrate that the coupling constant is highly dependent upon the orientation of the crystal with the incident laser beam and thus the strength of the phase conjugation process in the crystal is also closely linked to the orientation. This point will be discussed in the experimental set-up section in relation to the actual crystal orientation.

2.3 Optical Fibers

Optical fibers, able to guide light with low losses, make use of the concept of total internal reflection. Fibers generally consist of three components each serving different purposes as shown in Figure 3. The fiber consists of a core of fused silica glass (SiO_2), where most of the light is transmitted; a cladding layer with a lower index of refraction to cause total internal reflection; and an outer jacket which protects the two inner layers. This type of fiber is called step-index fiber for obvious reasons. There is a second type of fiber called graded-index fiber in which the refractive index decreases as one moves progressively outwards towards the jacket.[13] Of prime interest in step-index fibers is the difference between the indices of refraction of the core, and cladding because this difference is what leads to the total internal reflection. This difference is expressed relative to the refractive index of the core, and is given as $\Delta = (n_1 - n_2)/n_1$. Another important quantity is the normalized frequency which is defined as $V = k_o a(n_1^2 - n_2^2)^{1/2}$, where a is the core radius and $k_o = 2\pi\lambda$. The normalized frequency is important because it allows one to calculate how many modes the fiber will support.

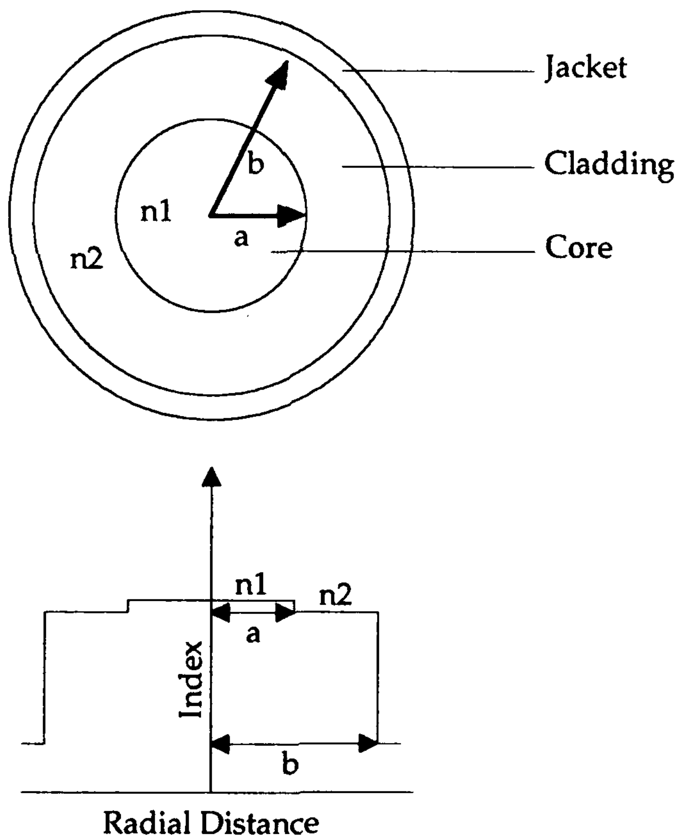

Figure 3. Fiber Cross Section and Refractive Index Profile

If $V > 2.405$, (which is the smallest solution to the Bessel function $J_0(V) = 0$) then it will support more than one mode. Fibers having a normalized frequency below this cutoff value, are known as single-mode fibers, while those with a higher value are multi-mode fibers. V is inversely proportional to wavelength, and directly proportional to core diameter, which indicates that for equal indices of refraction more modes will be supported for larger diameter fibers, or shorter wavelength lasers. The fiber used in this thesis, has a core diameter of 8.3 μm and the wavelength of the argon-ion laser is 514.5 nm, which results in a normalized frequency of 6.08 indicating that this is multi-mode fiber, able to support more than ten modes. Another important aspect of optical fiber to consider, especially with long fiber lengths, is attenuation of the pump beam within the fiber. The relationship between the input power and the output power, at the end of the fiber is given by

$$P_t = P_i \exp(-\alpha L) \tag{10}$$

where α is the attenuation constant or fiber loss. Typically the fiber loss is expressed in units of dB/km through the following equation.[13]

$$\alpha_{db} = -(10/L)\, \mathrm{Log}[P_t/P_i] = 4.343\, \alpha \tag{11}$$

The above relationship assumes perfect coupling into the fiber, which is impossible in practice. To account for imperfect coupling a coupling coefficient is included in the above relationship between input and transmitted powers. The coupling coefficient is the unattenuated power in the fiber divided by the incident power. The value of C which was used throughout this thesis, was C = 0.66-0.72, and was obtained from previous experiments performed at AFIT with the same fiber used here.[3] The attenuation constant, α_{db}, was also determined to be 16.4 dB/km ($\alpha = 3.78 \times 10^{-5}$ /cm) from the same source.

2.4 SBS in Optical Fibers

Stimulated Brillouin scattering is the process by which a light wave interacting with sound waves in a nonlinear medium cause the production of a backward traveling Stokes wave that has been downshifted in frequency by an amount equal to the frequency of the acoustic wave. It is similar to stimulated Raman scattering (SRS) in that the resultant Stokes wave has been downshifted by a value dependent upon the properties of the nonlinear medium. The fundamental difference between the two processes, which gives rise to significant disparities in threshold powers, frequency shifts etc. is that SRS involves optical phonons while SBS involves *acoustical phonons.*

Stimulated Brillouin scattering is essentially a scattering of a photon by a phonon and as such the laws of conservation of energy and linear momentum require that

$$\omega_a = \omega_i - \omega_s \tag{12}$$

$$\mathbf{k}_a = \mathbf{k}_i - \mathbf{k}_s \tag{13}$$

where the a, i and s subscripts denote the acoustic, pump and Stokes frequencies and wave vectors respectively. From equation 13 it is clear that one can derive the Bragg condition for the diffraction of photons by phonons

$$k_a^2 = k_i^2 + k_s^2 - 2\mathbf{k}_i \cdot \mathbf{k}_s \tag{14}$$

$$k_a^2 \approx k_i^2(1 + 1 - 2\cos\theta) \tag{15}$$

$$k_a^2 = 4k_i^2 \sin^2(\theta/2) \tag{16}$$

$$k_a = |\mathbf{k_a}| = 2k_i \sin(\theta/2) \tag{17}$$

where θ is the angle between the pump and Stokes waves. Using the relation $k_a=\omega_a/\upsilon_a$, where υ_a is the speed of sound within the medium, the downshift in frequency is determined to be[13]

$$\omega_a = |\mathbf{k_a}|\upsilon_a = 2\upsilon_a |\mathbf{k_i}| \sin(\theta/2) \tag{18}$$

It is apparent that the maximum value for ω_a will be obtained when $\theta = \pi$ which indicates that the maximum frequency shift will occur when the stokes and pump waves travel in opposite directions. As the frequency shift in the forward direction is zero, for the restricted case of optical fiber, the Stokes beam is scattered entirely in the backwards direction.

In the case of stimulated Brillouin scattering, the acoustic wave for the Bragg reflection given by equation 17 is generated by the light itself in the nonlinear medium. An acoustic wave can be thought of as a variation in density which satisfies the wave equation

$$\nabla^2\rho' - (1/\upsilon_a^2)(\partial^2\rho' / \partial t^2) = 0 \tag{19}$$

where ρ is the density, and the prime indicates a small perturbation from the essentially constant density, ρ_o, of the medium ($\rho = \rho_o + \rho'$). The purpose of this derivation is to determine how the light wave generates the acoustic wave (e.g. a light-induced density variation), so the addition of a source term, **f**, must be made. One would also like the ability to look at damping of the wave so a viscosity term, η, is also included. Once these changes are made the final wave equation is

$$\upsilon_a^2 \nabla^2\rho' + \eta \nabla^2(\partial\rho' / \partial t) - (\partial^2\rho' / \partial t^2) = \nabla \cdot \mathbf{f} \tag{20}$$

Here **f** is the force per unit volume due to the light in a charge neutral medium, and under certain simplifying conditions, this force per unit volume is

$$\mathbf{f} = \tfrac{1}{2} \gamma_e \nabla E^2 \tag{21}$$

where γ_e is a constant of the medium itself. The divergence of the forces is the variation in density due to an electric field.

$$\upsilon_a^2 \nabla^2\rho' + \eta \nabla^2(\partial\rho' / \partial t) - (\partial^2\rho' / \partial t^2) = \tfrac{1}{2} \gamma_e \nabla^2 E^2 \tag{22}$$

The polarization of the medium is given as $\mathbf{P} = (\varepsilon - \varepsilon_o)\mathbf{E}$ where the permittivity, ε, is a function of the density of the medium. If we break the polarization into linear and nonlinear parts, $\mathbf{P}_l$, and $\mathbf{P}_{nl}$, we can discard the linear portion as being irrelevant for our purposes and are left with a nonlinear polarization term of the form

$$\mathbf{P}_{nl} = \rho' (\partial\varepsilon / \partial\rho)\big|_{\rho_o} \mathbf{E} \tag{23}$$

where the partial integral is evaluated at ρ_o. Upon substitution of equation 22 into equation 23 and rewriting for **E**, the result is

$$\nabla^2\mathbf{E} - (1/c^2)(\partial^2\mathbf{E} / \partial t^2) = \mu_o(\partial^2\mathbf{P}_{nl} / \partial t^2) = (\mu_o\gamma_o/\rho_o)[\partial^2(\mathbf{E}\,\rho') / \partial t^2] \tag{24}$$

Equations 22 and 24 are coupled nonlinear equations for the density perturbation and the electric field which is what is desired.[13] From these equations, it is possible to see how an incident light wave can generate a density perturbation which in turn will create an oscillation in the polarization of the medium which will create an oscillation in the index of refraction. This oscillation in the refractive index is the grating upon which the light wave is scattered into the backward traveling Stokes beam. Because the grating is moving with the speed of sound in the medium, the scattered beam is Doppler shifted in frequency by an amount given by

$$\nu_S = \omega_a / 2\pi = 2n\, \upsilon_a / \lambda_i \qquad (25)$$

which is the frequency of the acoustic wave in the medium. In this case λ_i, is the wavelength of the pump beam.

The Brillouin gain coefficient, $g_S(\nu)$, characterizes the growth of the Stokes wave in the optical fiber. If the acoustic wave is assumed to decay exponentially as $\exp(-t/T_S)$, then the gain exhibits a Lorentzian spectral profile of the form

$$g_S(\nu) = g_S(\nu_S)\, (\Delta\nu_S/2)^2 \,/\, [(\nu - \nu_S)^2 + (\Delta\nu_S/2)^2] \qquad (26)$$

where $\Delta\nu_S$ is the FWHM linewidth and $g_S(\nu_S)$ is the peak value of the gain coefficient which has been shown to be

$$g_S(\nu_S) = 2\pi n^7\, p_{12}{}^2 \,/\, c\lambda_i{}^2\, \rho_o \upsilon_a\, \Delta\nu_S \qquad (27)$$

where p_{12} is the longitudinal elasto-optical coefficient and ρ_o is the density of the optical fiber.[14] $\Delta\nu_S$ has been shown to depend upon the Brillouin shift, varying slightly faster than ν_s^2, while ν_s in turn varies inversely with the pump wavelength indicated by equation 25. $\Delta\nu_s$ as a result is proportional to λ_i^{-2}. As the wavelength increases, the gain bandwidth narrows which negates their inverse behavior in the denominator of equation 27. The result is that the Brillouin gain coefficient is essentially independent of the wavelength of the pump beam.[13] The Brillouin gain coefficient is also typically much larger than the Raman gain coefficient at a given wavelength. As a result SBS is usually much more easy to initiate than SRS because of the lower powers required for onset. To determine a theoretical value for SBS threshold it is necessary to begin by considering the interaction of the pump and Stokes waves. From Maxwell's equations one can rigorously derive these interaction equations which are essentially statements of conservation of photons (energy) in the SBS process. The results are

$$dI_s / dz = -g_s I_i I_s + \alpha I_s \tag{28}$$

$$dI_i / dz = -g_s I_i I_s - \alpha I_i \tag{29}$$

where the subscripts s, and i indicate the Stokes and pump beams respectively, g_s is the Brillouin gain coefficient, z is the axial direction along the fiber, and where, α, the fiber loss has been assumed to be equal for both the Stokes and pump waves. This assumption is valid due to the relatively small Billouin shift (i.e. $\omega_s \approx \omega_i$). Once the SBS threshold has been reached, a significant portion of the pump beam is transferred into the Stokes beam. To solve the above equations with the inclusion of pump depletion requires an exact solution, but a much more simplified solution is possible if pump depletion is neglected. After neglecting pump losses beyond attenuation within the fiber the result is

$$I_s(0) = I_s(L)\exp(g_s P_o L_{eff} / A_{eff} - \alpha L) \tag{30}$$

where the input power, $P_o = I_i(0)A_{eff}$, $I_i(0)$ is the pump intensity at $z = 0$, and A_{eff} is the effective core area of the fiber. The effective interaction length is given by[13]

$$L_{eff} = (1/\alpha)[1 - \exp(-\alpha L)] \tag{31}$$

One definition for the Brillouin threshold is that input power at which the Stokes power equals the pump power at the fiber output or[15]

$$P_s(L) = P_i(L) = P_o \exp(-\alpha_i L) \tag{32}$$

Using the above equation and assuming that the Brillouin gain spectrum is Lorentzian, the critical pump power for SBS ons . P_o^{cr}, is found to be

$$P_o^{cr} \cong 21\,[A_{eff} / L_{eff}\, g_s(\nu_s)] \tag{33}$$

Although the value of 21 is approximate the important aspects of the critical power relation is that required power increases for fibers of larger diameter, and decreases for shorter fiber lengths.

2.5 The Phase Conjugation Nature of SBS

Finally, it is necessary to consider how stimulated Brillouin scattering is able to phase conjugate. While the theoretical basis for PC is complicated, the fundamental aspect is that the backwards scattered Stokes beam will most effectively milk the pump beam when it is it's phase conjugate replica. The theory behind this capability was first presented by Zel'dovich in the 1972 paper where phase conjugation by SBS was reported. The essence is that in the limit of low scattering the nonlinear Maxwell's equations become linear in the backscattered optical field. The linear equations have several solutions which are modes in an equivalent sense as the Gaussian-Hermite modes are solutions to the linear Maxwell's equations in free space. These modes, however, have complex propagation vectors meaning that the solutions will have gain under Stokes scattering.[16]

The argument for phase conjugation begins with describing the propagation of the Stokes wave in the backwards direction (-z)

$$E_S(\mathbf{r}\perp, z) = \varepsilon_S(\mathbf{r}\perp, z)\, e^{ik(s)z} \tag{34}$$

by a parabolic equation

$$(\partial\varepsilon_S / \partial z) + (i/2k_S)\nabla^2\varepsilon_S + \tfrac{1}{2}\, g(\mathbf{r}\perp, z)\varepsilon_S = 0 \tag{35}$$

where $g(\mathbf{r}\perp, z) = A\,|E_i(\mathbf{r}\perp, z)|^2$ and A is a constant dependent upon the velocity of sound and the sound absorptive coefficient of the medium, the mass density, the photoelastic constant, and the wavelength of the pump beam.[17] The $\mathbf{r}\perp$ is perpendicular from the axial (z) direction at the particular position z. If the terms with gain are neglected then the pump field

$$E_i(\mathbf{r}\perp, z) = \varepsilon_i(\mathbf{r}\perp, z)\, e^{ik(i)z} \tag{36}$$

satisfies an equation that is the complex conjugate of equation 32

$$(\partial \varepsilon_i \ / \ \partial z) - (i/2k_i)\nabla^2 \varepsilon_i = 0 \tag{37}$$

when the small difference between k_s^{-1} and k_i^{-1} is neglected. It is necessary to consider a set of functions, $f_i(r\perp, z)$, $i = 0, 1, 2, \ldots$, which satisfies both the orthogonality relation at the position $z = z_o$ and satisfies an equation that describes the propagation of the complex conjugate field of the laser. In this case such an equation is the complex conjugate of equation 37.

$$(\partial f_i \ / \ \partial z) + (i/2k_i)\nabla^2 f_i = 0 \tag{38}$$

By satisfying both requirements, it is assured that the orthogonality relation will hold at any section along the fiber. It is necessary to choose a function $f_o^*(r\perp, z)$ that coincides (within a multiplicative constant) with the laser field i.e., $\varepsilon_i(r\perp, z) = Bf_o^*(r\perp, z)$. The remainder of the set, $f_i^*(r\perp, z)$, $i = 1, 2, \ldots$, is arbitrarily chosen from the orthogonality relation. The field of the backscattered Stokes signal is represented as an expansion of the form

$$\varepsilon_s(r\perp, z) = \Sigma \ C_i(z) \, f_i(r\perp, z) \tag{39}$$

where the $C_i(z)$ coefficients are derived from the relation

$$(dC_i(z)/ \ dz) + \tfrac{1}{2}\Sigma \ g_{ik}(z) \, C_k(z) = 0 \tag{40}$$

where both summations are from $i = 0$ to ∞, and where

$$g_{ik}(z) = AB^2 \int dr\perp \ | f_o(r\perp, z) |^2 \, f_i^*(r\perp, z) \, f_k(r\perp, z) \tag{41}$$

The constant A is a proportionality constant for the gain used in equation 35, and B is the multiplicative constant used earlier. Essentially, one is looking for the solutions to equations 40 and 41. This is rather complicated and unnecessary, because it is sufficient to state the following. In the case where the laser field fluctuates strongly as a function of $\mathbf{r}\perp$, the gain of the zeroth function g_{oo} will be on the order of 2-3 times that of all the other g_{ik}.[1] This means that the amplitude $C_o(z)$, will increase more rapidly with distance within the fiber than the others. After a sufficient distance the field will be given by

$$\varepsilon_S(r\perp, z) = \sum C_k(z)\, f_k(r\perp, z) \cong C_o(z)\, f_o(r\perp, z) = [C_o(z)/B^*\varepsilon_i^*(z)] \qquad (42)$$

which satisfies our requirement that the Stokes beam be the phase conjugate of the input pump beam.

2.6 Feedback from a $BaTiO_3$ Crystal

This thesis is an extension of previous work that has been done at AFIT, primarily work that attempted to create a Brillouin ring laser using optical fiber, which would lower the SBS threshold in the fiber while achieving phase conjugation.[4] The previous work was successful in reducing the power required for SBS onset but found that the ring cavity configuration for the Stokes beam did not produce a phase conjugate replica of the input pump beam. This thesis has been an attempt at creating a similar feedback mechanism that it is hoped will demonstrate PC through SBS.

Although long fiber lengths lengths have a lower SBS threshold, phase conjugation has not yet been shown to result. Phase conjugation from SBS in short fiber lengths (under 10 meters) has been demonstrated using a pulsed laser, but the penalty is a much higher input power.[18] The ring cavity used in the previous experiment was an attempt, through feedback, to lower the SBS threshold enough to use a cw laser in a short length of fiber. Although the SBS threshold was lowered, the lack of phase conjugation is believed to have been due to the condition of the phase front upon emerging from the back end of the fiber. This output was coupled into the front of the fiber, but apparently after making the trip through the fiber it no longer retained the same phase front as the Stokes beam emerging from the front of the fiber. The substitution of the barium titanate crystal has been an attempt to remedy the problem of dissimilar phase fronts.

In Figure 4 the essential approach is outlined. The argon-ion pump beam enters from the top of the figure, passing through the left beam splitter into the fiber. From the aforementioned results, the resulting Stokes beam is not at this point the phase conjugate of the input pump beam. This Stokes beam leaves the fiber, traveling up in the figure, towards the same beam splitter and is partially reflected through the second beam splitter onto the face of the barium titanate crystal. The resulting beam that is reflected from the crystal has been shown to be the phase conjugate of the Stokes beam. This phase conjugate beam travels back through the right beam splitter, and is partially reflected by the left into the fiber where, from the distortion correction principle explained in section 2.1, the phase fronts will be coincident. It is believed that because the phase profiles are similar, if not identical, this cavity formed with the crystal will lower the SBS threshold and allow for the Stokes beam to be phase conjugated. The final phase conjugated output is to be measured at the detector below the right beam splitter.

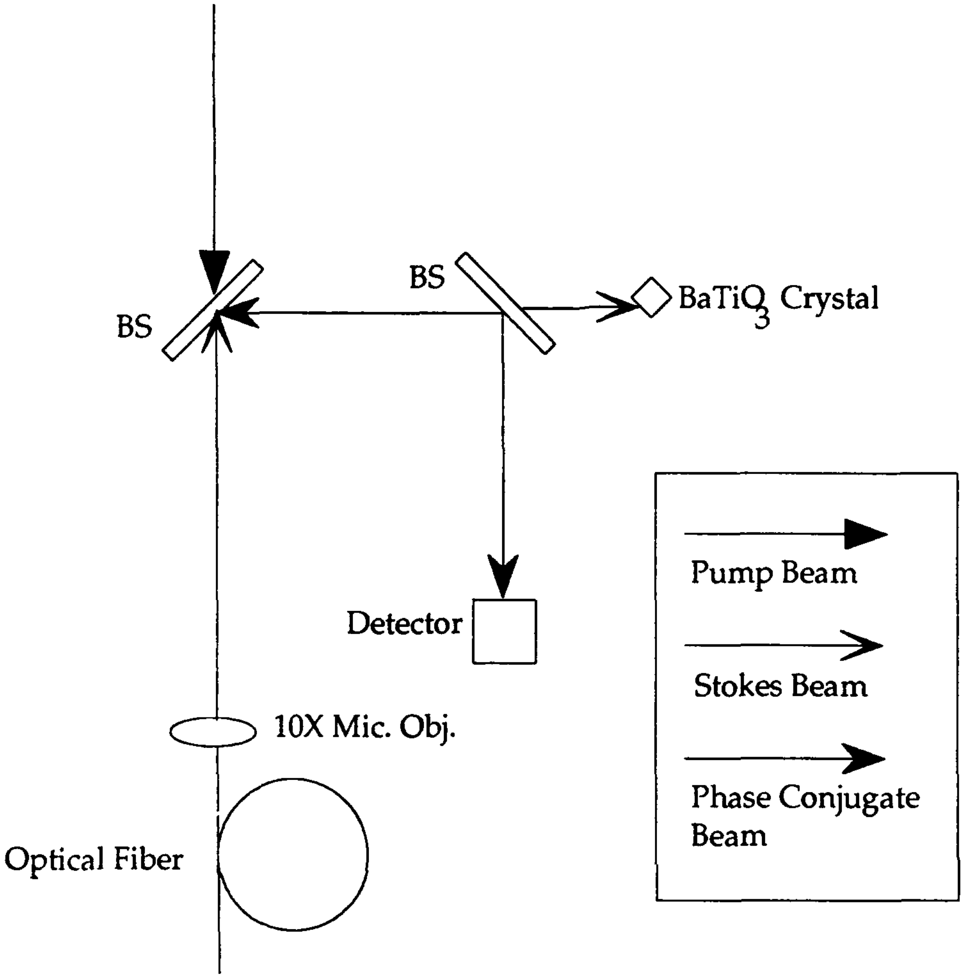

Figure 4. Feedback and Phase Front Preservation Using the $BaTiO_3$ Crystal

III. Experimental Setup

This chapter describes the equipment used within the experiment to determine the threshold for SBS in the fiber and to test for optical phase conjugation of the Stokes beam with the aid of the barium titanate crystal.

3.1 Determination of SBS Onset

Figure 5 shows the setup for the portion of the experiment to determine if the inclusion of the phase conjugating crystal lowers the threshold power needed to begin SBS in the optical fiber. The laser was a Spectra-Physics argon-ion laser, Model 171. It was tuned to a wavelength of 514.5 nm and was restricted to single mode operation by the inclusion of an internal etalon. Its nominal output in such a configuration was 2.0 watts. To phase conjugate in $BaTiO_3$ crystal requires horizontally polarized light, while the output from the laser was vertically polarized. The inclusion of the half-wave plate was made to alter the polarization to the required orientation. The laser pump beam entered the fiber through the first 10X microscope objective and the throughput was coupled out of the fiber at the other end by a similar microscope objective. Both microscope objectives were on rotating-translating stages with attached fiber mounts which allowed for precise coupling of the input into the fiber. The Stokes beam was reflected by beam splitter (BS) 2 and was transmitted through BS 3 where it illuminated the crystal face at an angle of approximately 45 degrees. The resulting backscattered phase conjugate beam was reflected off of BS 3 into the detector.

Four power meters (Newport Model 815) were used for simultaneous measurements of the input to the fiber, the reflected stokes beam, the throughput of the fiber, and the backscattered phase conjugate beam from the

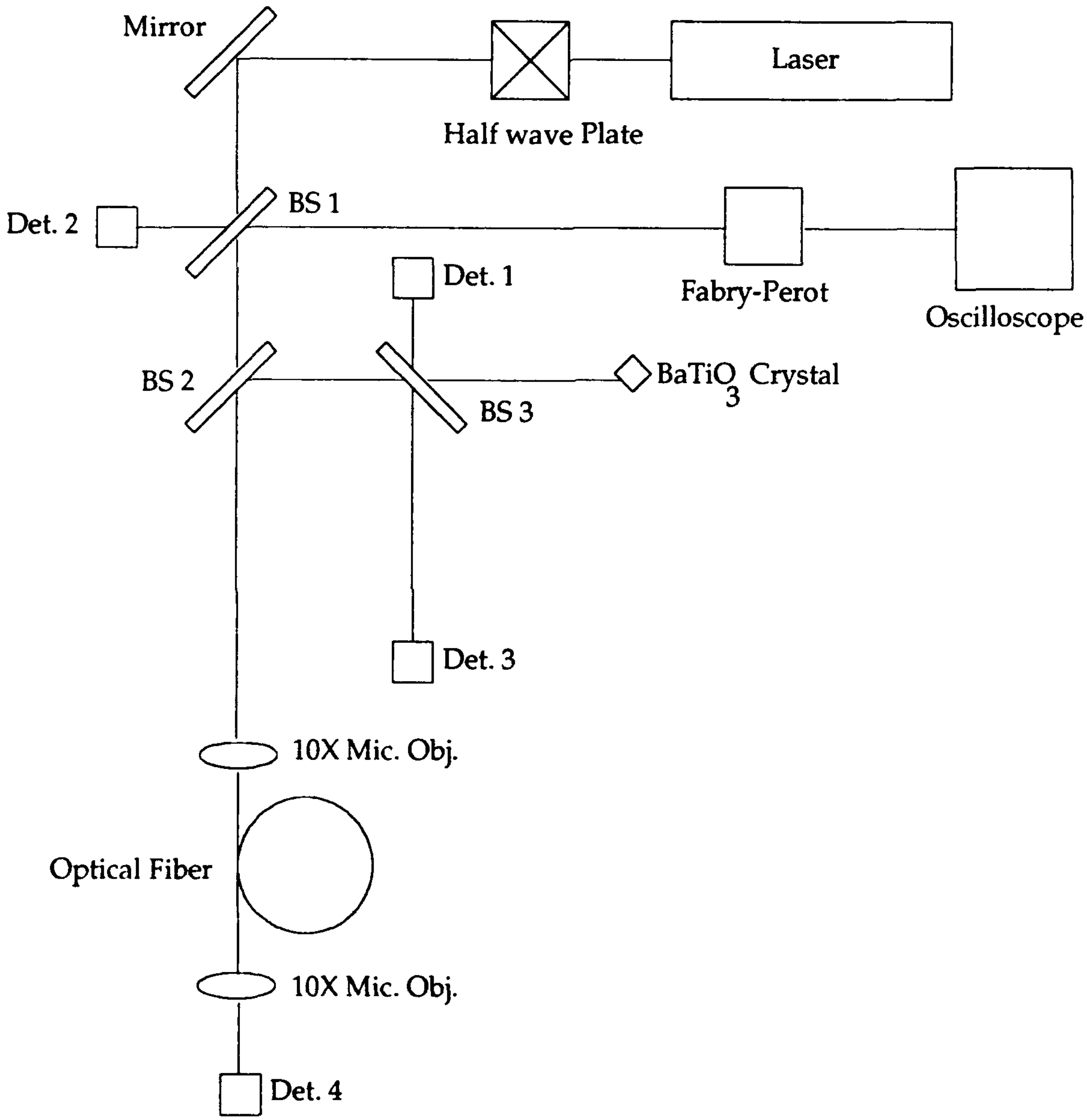

Figure 5. Experimental Setup for Determination of SBS Threshold Power

crystal. These power meters were connected to a personal computer (Zenith Z-248) which recorded the various power levels using the program Tlablog. For determination of the presence of a Stokes beam, a Fabry-Perot spectrum analyzer (Tropel Model 240) was connected to an oscilloscope (Lavoie Laboratories Model LA 265A) to display the spectrum of the Stokes peak.

The optical fiber used in the experiment was Corning Corguide SMF-28 CPC3 step-index fiber, with a core diameter of 8.3 μm. At 514.5 nm, the fiber is able to support 10 fiber modes. To prepare the fiber for use in the mount the outer jacket was stripped away after the ends had been cleaved. The condition of the fiber ends was inspected under a microscope to ensure that they were flat and that there would be maximum coupling of the laser input.

Proper coupling of the laser into the fiber was of prime importance because slight misalignment could result in little or no transmission through the fiber. After the laser was aligned so that the beam was parallel to the lab bench, the other components were positioned so that the beam continued to travel horizontally. This ensured that coupling into the fiber would be simplified. Proper coupling was highly dependent upon the focal length of the objective, as a result the axial distance (z-direction) between the fiber face and the objective was of critical importance. The proper position of the end of the fiber in the x and y directions was in turn dependent upon the position in the z direction, so that after a process of alternating among the axes, good alignment was achieved. As a final check, the throughput was maximized at detector 4.

The $BaTiO_3$ crystal that was used had 45^o-cut crystal faces as opposed to the Z-cut face crystal that was explained in section 2.3 but the degenerate four-wave mixing process within the crystal is the same. Similarly, the onset of phase conjugation in the 45^o-cut crystal was dependent upon proper orientation of the crystal with respect to the input laser beam. The orientation of the crystal is the same as in Figure 2 except the C axis is rotated 45^{o} to the one shown. The onset of phase conjugation was observed by reading detector 1, which upon PC backscatter from the crystal would register a large increase in power relative to ambient levels.

To determine the power required for SBS onset two sets of measurements were made; one set with the crystal in place and another set where the crystal was blocked so that the SBS onset was entirely due to the optical fiber alone. For those measurements with the crystal in place, the power was increased above the SBS threshold until the Stokes spike was observed on the oscilloscope, and the phase conjugate backscatter was observed coming from the crystal at detector 1. Once a steady state was achieved the power was slowly lowered while the four detectors recorded the respective powers. The results from these measurements will be presented in the results and conclusion section.

3.2 Test for Phase Conjugation in Optical Fiber

To test whether or not the Stokes beam was phase conjugated several changes were made to the previous setup. The method used was to measure the percent transmission through a pinhole onto a detector and was employed in the previous work at AFIT of which this thesis is a follow-up. In parallel with the distortion correction ability of a phase conjugate beam discussed in section 2.1, it was thought to check for PC by aberrating the beam that was input into the fiber and determining if the SBS process was able to correct this distortion. In this case the "distorting medium" was two lenses which were used to defocus the beam before entering the fiber. The idea was that a diverging beam would transmit less power than a collimated beam when focused onto a pinhole placed

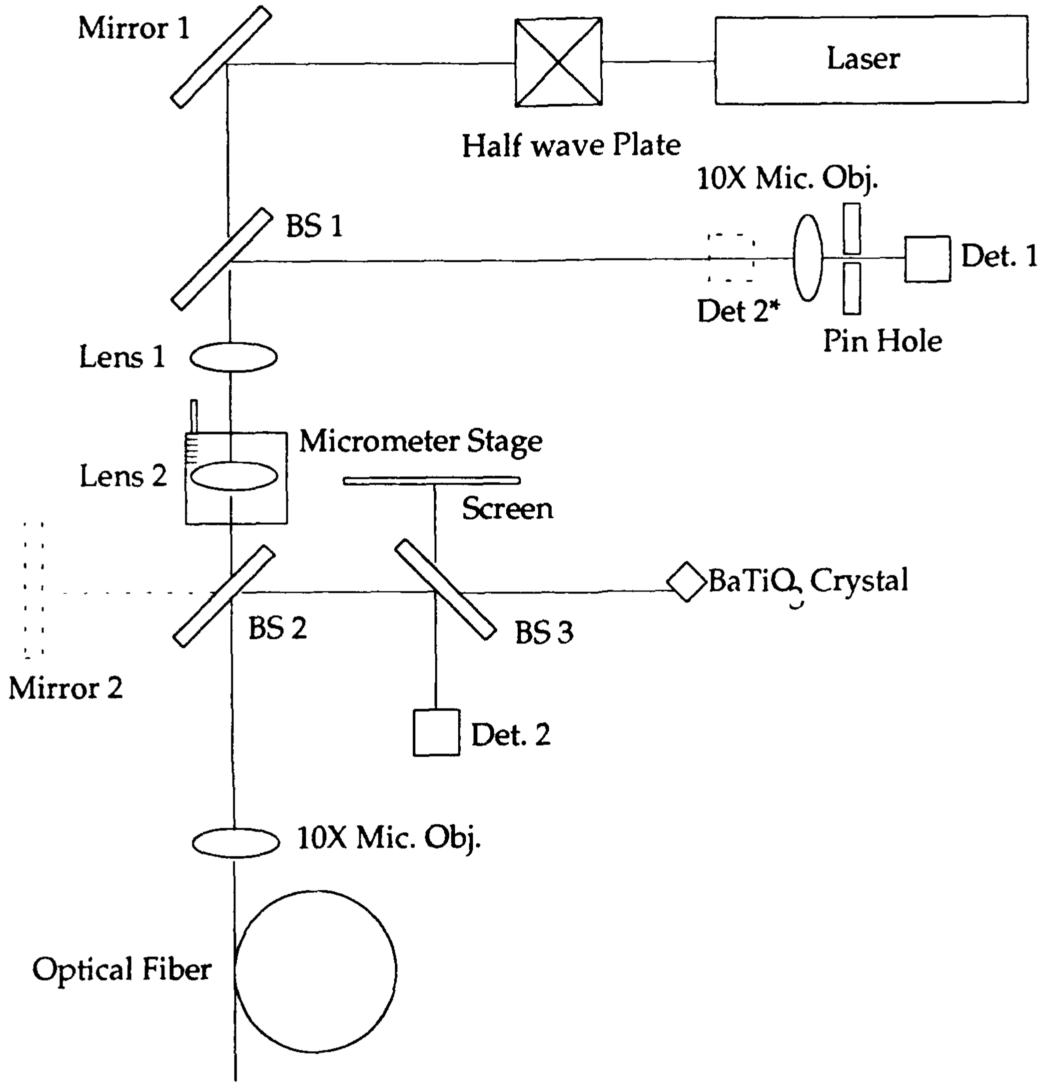

Figure 6. Experimental Setup for Testing for Phase Conjugation

in the focal plane. If the Stokes beam were the phase conjugate of the diverging input beam it would be collimated after passing back through the lenses and so the percent transmission through the pinhole would remain constant. Figure 6 shows the modified setup. Two lenses were inserted between BS 1 and BS 2 to diverge the laser beam. Lens 1 had a focal length of 75.6 mm and was fixed in position. The second lens had a focal length of 100 mm and was mounted upon a micrometer stage which could be precisely controlled. These lenses were initially placed 17.56 cm apart so that the laser beam would be collimated after passing through them. A 25μm pinhole and 5X microscope objective combination with detector was positioned to the right of BS 1 to measure the power transmitted through the pinhole.

After the additional components were properly aligned on the bench the proper position of the two lenses for collimated output was insured by comparing the beam spot size on either side of the lenses. SBS was then established and the pinhole position was adjusted for maximum transmission as indicated by detector 1. The $BaTiO_3$ crystal was also aligned for maximum phase conjugate reflection. As a control to see the behavior of a Stokes beam that was not phase conjugated, mirror 2 was positioned to the left of BS 2 and was aligned to reflect maximum power through the pinhole. This mirror would provide no phase conjugation at all and so any diverging beam reflected off of it would still be diverging as it passed through the pin hole. The pin hole would allow increasingly less power through as the lenses were moved from the afocal position.

Three sets of data were taken with this setup; one set with only the mirror in position as explained above, one set with the crystal and fiber aligned for feedback from the crystal, and finally a set with the crystal blocked to observe the phase conjugation ability of the fiber alone. The second lens was moved in increments of 0.1 mm while the output from the power meters was recorded on the computer. The power readings at the second detector position were correlated to the desired position at Det 2* by placing power meter Det 1 at position Det 2* and recording measurements from both Det 1 and Det 2 while Lens 2 was moved in 0.1 mm increments. The results from these measurements are presented in the following chapter.

IV. Results and Conclusions

4.1 Results of SBS Threshold Power Measurements

Several threshold power measurements were made in three lengths of optical fiber; 50, 150 and 200 meters. For each length of fiber runs were made with the fiber alone and with the $BaTiO_3$ crystal in place. Figures 7 and 8 show the behavior of the backscattered power and the transmitted power as a function of coupled input power for the case of fiber alone and fiber with the crystal. In both cases the transmitted power increases linearly while the backscattered power remains almost zero until just under 600 mW of coupled power. At this point the SBS threshold has been reached and the backscattered component rapidly increases. Beyond this point the pump power is being converted into Stokes power and so the transmitted power levels off, and then actually decreases. The reason for this is that the Stokes conversion efficiency is partially dependent upon both the SBS intensity and the pump intensity and so the Stokes wave is able to drain the pump beam at a slightly higher rate than the increase in coupled input power.

The results of the 200 meter fiber length measurements are presented in Figures 9 and 10, and exhibit much the same behavior. Because of the increased length of the fiber, the SBS process is initiated at a much lower power level than the with the 50 meter fiber in accordance with the relationship established by equation 30. For both conditions of fiber alone and fiber with the crystal, SBS onset occurred at approximately 200 mW coupled input power.

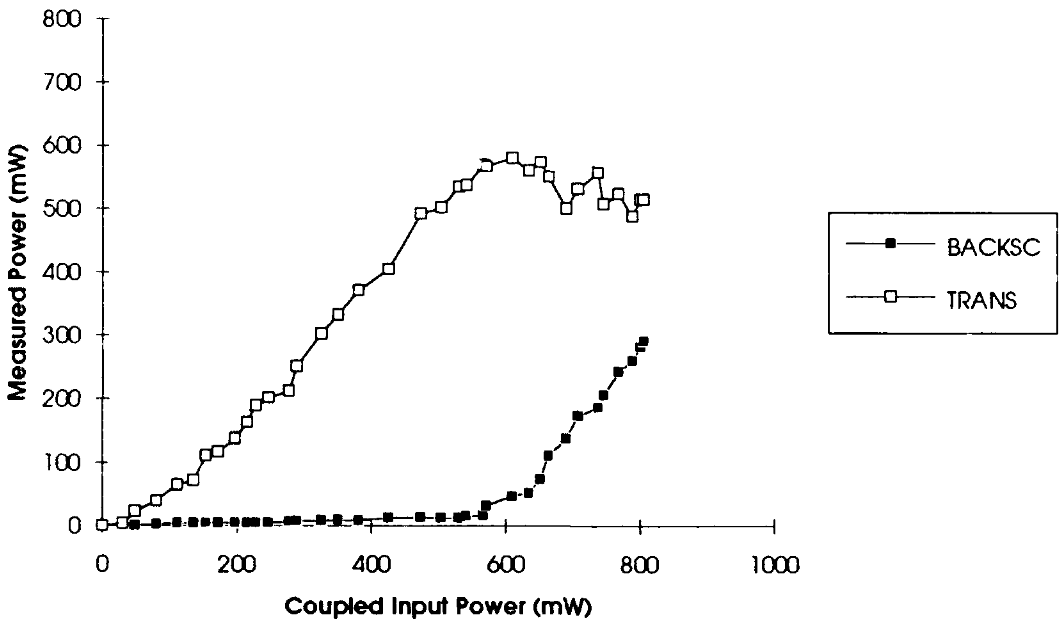

Figure 7. Transmitted and Backscattered Powers as a Function of Coupled Input Power for 50 Meter Fiber With Barium Titanate

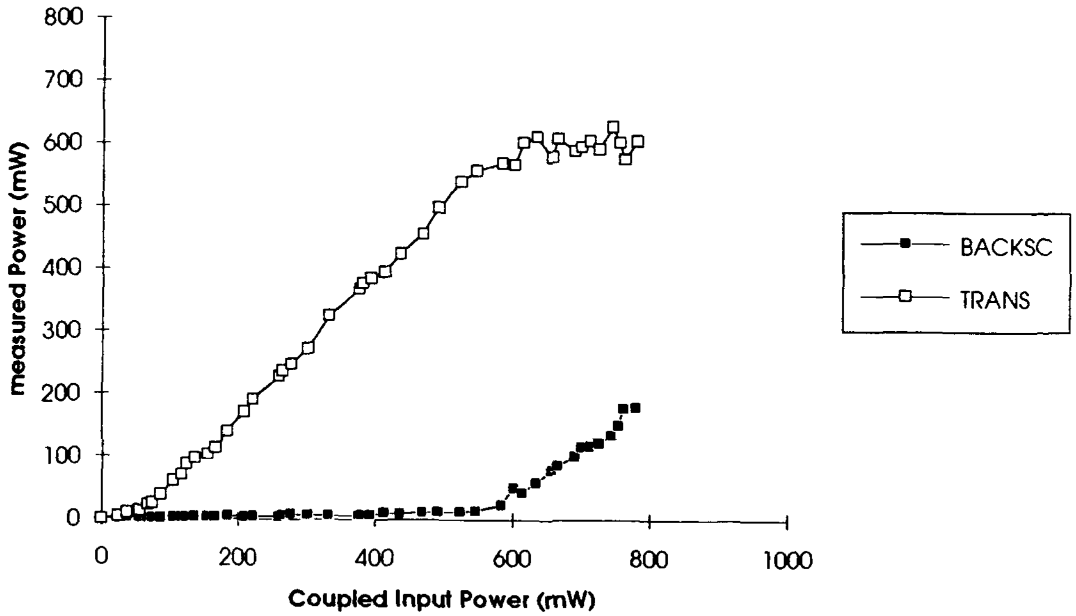

Figure 8. Transmitted and Backscattered Powers as a Function of Coupled Input Power for 50 Meter Fiber Without Crystal

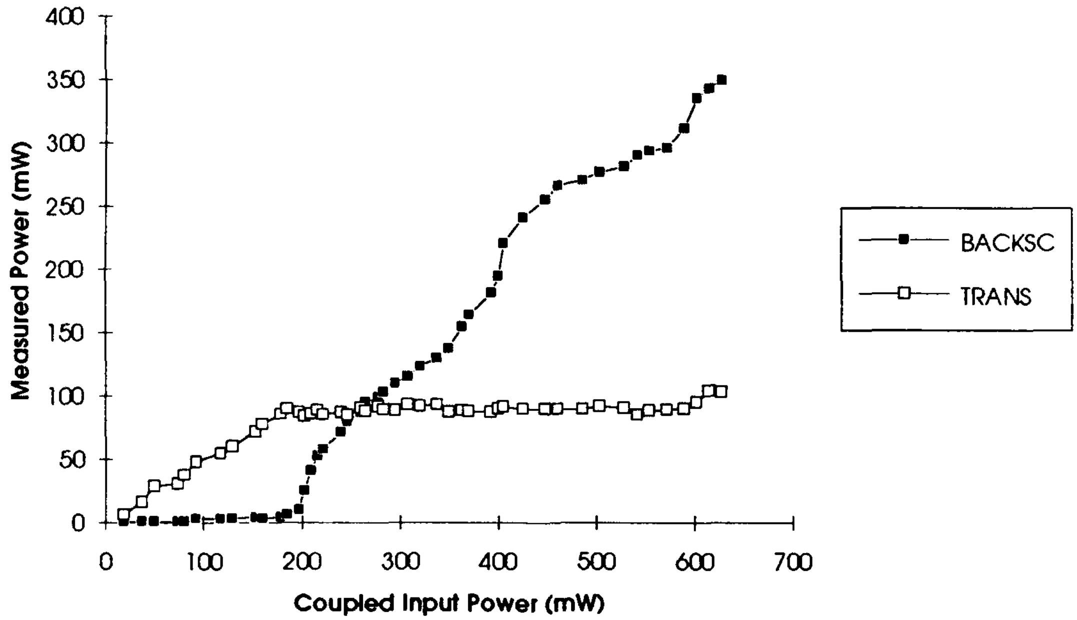

Figure 9. Transmitted and Backscattered Powers as a Function of Coupled Input Power for 200 Meter Fiber With Barium Titanate

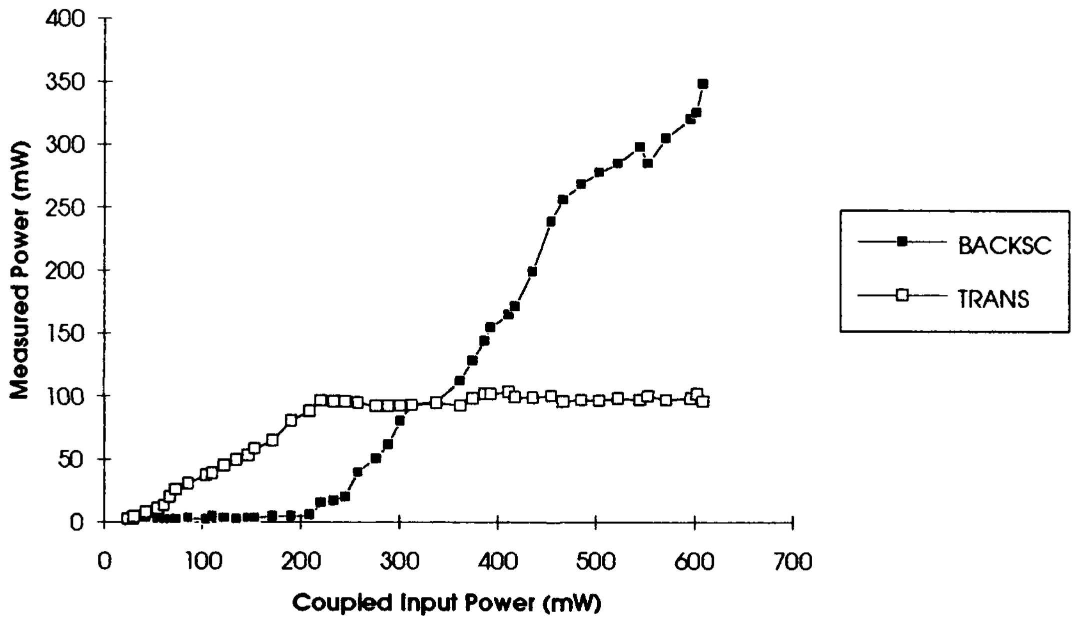

Figure 10. Transmitted and Backscattered Powers as a Function of Coupled Input Power for 200 Meter Fiber Without Crystal

In Figure 11, and Table 1, the threshold powers for SBS onset are compared for the three fiber lengths. The required powers for onset match favorably with values from previous measurements done at AFIT[3]. It is also clear that there is no discernible difference between the powers required for onset with the fiber alone, and when the $BaTiO_3$ crystal is in place.

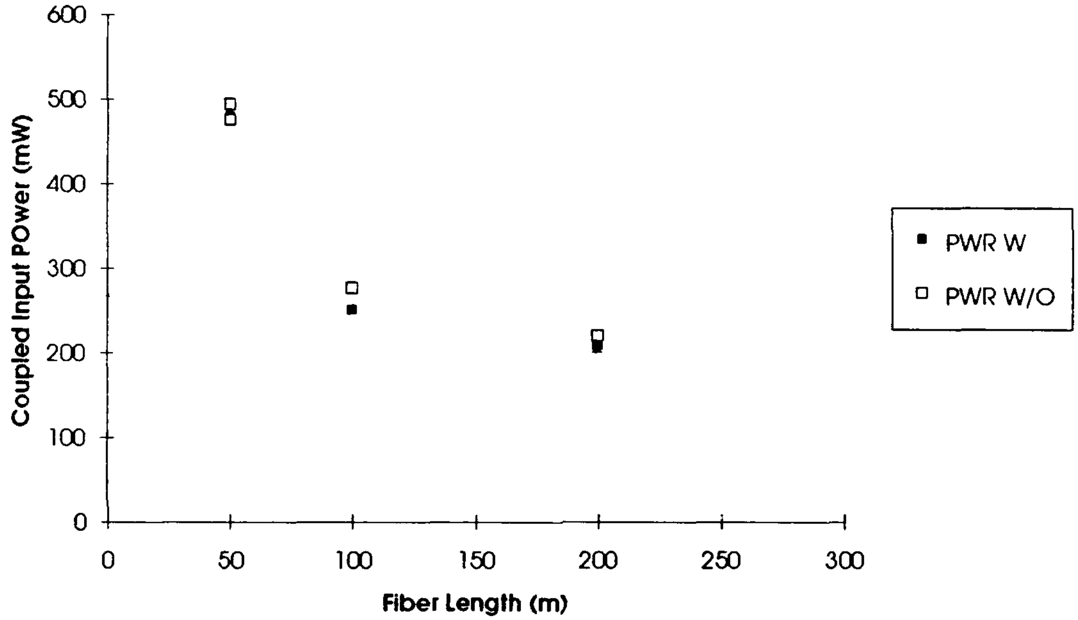

Figure 11. SBS Thresholds at Three Fiber Lengths

Fiber Length (m)	w/x-tal Threshold (mW)	w/o x-tal Threshold (mW)
200	205 ± 9	220 ± 10
200	208 ± 8	
100	251 ± 12	276 ± 14
50	476 ± 13	475 ± 15
50	480 ± 11	494 ± 12

Table 1. SBS Threshold Powers

4.2 Phase Conjugation Results

This section presents the results of the phase conjugation measurements in the optical fiber of 200 meter length. These results are presented in Figure 12. The figure shows the percentage of power that was transmitted through the pin hole as a function of displacement from the afocal lens position. Three curves are included, one for the mirror alone, one for the fiber alone, and one for the fiber and barium titanate crystal combined. If phase conjugation did occur the curves would be relatively flat indicating that the amount of power transmitted through the pinhole was constant as the lens was moved. Because the mirror provided no phase conjugation ability, the percent of light transmitted became progressively worse as the second lens was moved out of position, and the other curves should be compared with this curve as a standard of phase conjugation ability. All three curves showed the same behavior as the second lens was moved from the afocal position, which indicates that no phase conjugation occurred, either for the fiber alone, as was expected, or after the addition of the crystal.

Additional results were obtained for fiber lengths of 50 and 100 meters to determine the effect of fiber length. For both lengths the results were nearly identical to those shown in Figure 12, indicating that no phase conjugation occurred.

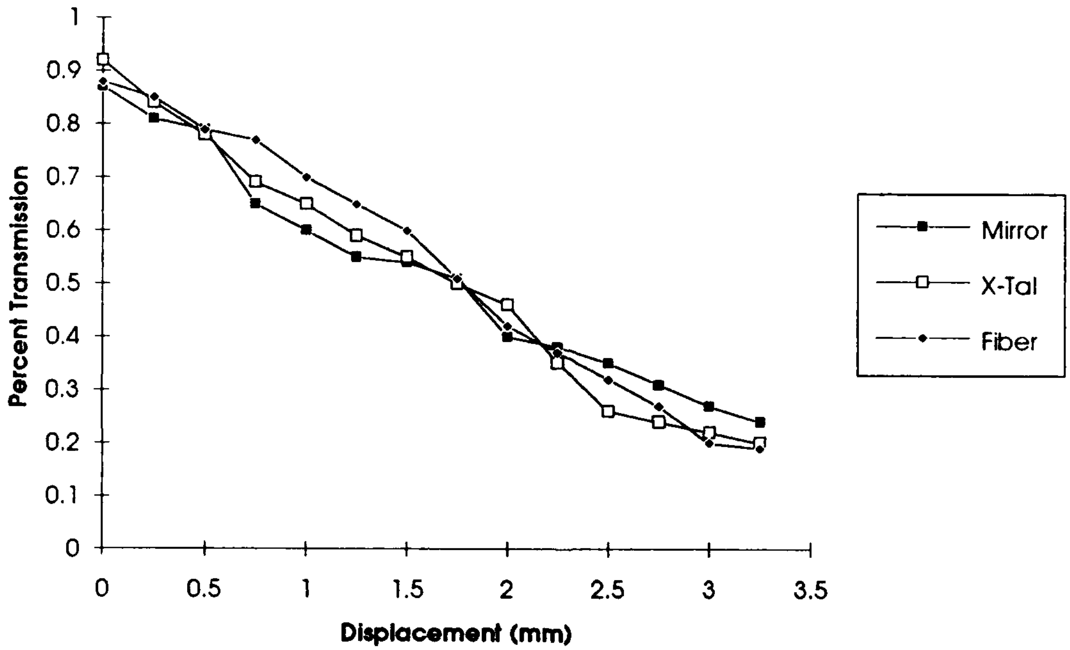

Figure 12. Percent Power Transmission vs Lens Displacement

4.3 Conclusions

The objective of this thesis has been twofold. One was to determine whether the addition of the phase conjugating barium titanate crystal would lower the power required for SBS in optical fiber. For the lengths of fibers used here, no reduction in threshold power was noticed, and the power evolution was similar to that of previous experiments. The second, more important, goal was to see if the barium titanate based phase conjugate cavity for the Stokes beam would enhance the generation of the phase conjugate Stokes beam in the fiber. The results presented here indicate that the addition of the $BaTiO_3$ crystal did not lead to phase conjugation of the backscattered Stokes beam.

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The goal of this thesis was to obtain phase conjugation in multi-mode optical fiber via stimulated Brillouin scattering (SBS) with the aid of a barium titanate crystal which formed a phase conjugate cavity for the Stokes beam. SBS was demonstrated but the SBS threshold was unaffected by the presence of the barium titanate crystal and no evidence for the presence of phase conjugation in the optical fiber was obtained.

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