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INVESTIGATION OF THE PULSE-TO-PULSE PHASE COHERENCE OF CARBON D--ETC(U)
JAN 80 C E HALFORD DAAG29-79-C-0018

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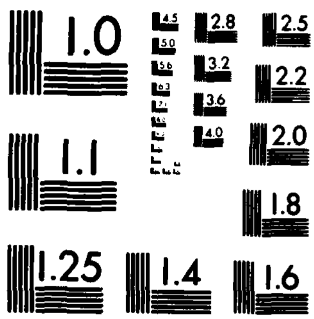

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INVESTIGATION OF THE PULSE-TO-PULSE PHASE COHERENCE OF CARBON DIOXIDE LASERS

FINAL REPORT

To
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Durham, North Carolina

For

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By

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January, 1980

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ABSTRACT

The phase coherence properties of pulsed carbon dioxide lasers are analyzed. Experimental results for a self-pulsing helium neon ring laser are presented and used to calculate the average phase coherence time for that system. Experimental factors are the primary limitations for phase coherence. These factors influence the phase by altering the resonant cavity by mirror motion or by index of refraction changes. The importance of these two factors are assessed for high power TEA lasers using the experimental results of others [1, 6]. A novel technique of active phase correction for correcting the phase of pulsed lasers is presented.

FOREWORD

Three graduate students contributed to the research reported here. Two received Master of Science degrees and the third is still pursuing graduate studies. They are William Dabbs, Melinda Watkins and Frances Wong. Their contribution to this research is gratefully acknowledged, particularly, their curiousity and piercing questions. In addition, helpful discussions were held with Dr. John Stettler and Dr. William Gamble of the Laser Radar Laboratory of the Army Missile Command, Redstone Arsenal, Alabama.

Introduction

Mode locked lasers have been studied extensively by a number of investigators. Typically, the output of these laser systems consists of a train of short, equally spaced pulses. The duration of the pulses is determined by the active medium and is usually a nanosecond or less. The spacing is determined by the round trip cavity length and is generally tens of nanoseconds. Of the many possible applications for such pulse trains, the one of major interest in this report is range doppler radar. It can be shown that a train of pulses of one nanosecond duration and twenty nanosecond spacing can be effectively utilized in a laser radar. The use of heterodyne detection provides a high degree of sensitivity along with valuable doppler information. Signal-to-noise ratios can be further enhanced by a coherent integration for the same range cell of the different pulses. Thus, the pulses from the laser system must possess phase coherence in order to effectively utilize heterodyne detection. If a cw local oscillator is used, one would like for the phase of each pulse in the transmitted train of pulses to have a fixed relationship with the phase of the local oscillator. Experimental care must be exercised to generate high power pulse trains with good pulse-to-pulse phase coherence.

The subject of pulse-to-pulse phase coherence is not widely reported in the literature. However, the related subject of frequency stability is well studied. Thus, it is possible to utilize reported results regarding frequency stability to predict phase coherence. An almost sinusoidal signal can be represented by

$$E(t) = E_0 \cos[\omega_0 t + \phi] \qquad (1)$$

where E_0 is the amplitude, ω_0 is the radian frequency, and ϕ is the phase. If ϕ is a function of time, then the radian frequency is

$$\omega = \omega_0 + \frac{d\phi}{dt} \qquad (2)$$

since the frequency is defined as the time rate of change of the argument of the sinusoid. If ω_0 is a function of time as well, then

$$\omega = \omega_0 + \frac{d\omega_0}{dt} t + \frac{d\phi}{dt} \qquad (3)$$

Experimentally, it is usually not possible to discern whether changes in frequency are a result of the second term or the third term of Eqn. 3, or from some combination of the two. Thus, discussions of the experimental factors that influence pulse-to-pulse phase coherence can be based on the extensive literature regarding frequency stability (see for example [1-4]).

One successful technique for the production of high power, coherent pulses is to utilize a low power very stable oscillator to control a higher power section. The lower power stable signal is injected into a higher power section, usually in a ring configuration, to achieve injection locking [5]. There are many experimental variations but they all share the feature that the phase coherence and frequency stability are dominated by the lower power oscillator within certain operating conditions [1,6]. At present, the most promising high power section is a TEA laser so a discussion of the phase coherence properties of injection locked TEA lasers is included in this report.

The final section of this report discusses a novel suggestion for an active phase correction system. Certain phase instabilities can possibly be corrected by judiciously changing the path length traversed by the pulses. Obviously, a scheme for detecting phase coherence is essential for this correction process and one is presented in that section. That detection scheme was reported independently by Jacobs, et al. [6]. Several remaining design questions are discussed as well as a suggested study of the statistics of phase coherence in a pulsed laser system.

Fundamentals of Pulse-to-Pulse Phase Coherence

This section of the report discusses some of the experimental manifestations of a pulse train possessing a degree of pulse-to-pulse phase coherence. It will be shown that the degree of coherence can be estimated from the spectrum of the pulse train. A train of pulses with no phase coherence will have a spectrum with a width that is inversely related to the time duration of the individual pulses. This width in the frequency domain is often limited by the gain characteristics of the active medium. A train of phase coherent pulses will have a spectrum that exhibits components within the overall width that is related to the pulse duration. The width of the individual components is inversely related to the time interval over which the pulses maintain phase coherence. Figure 1 illustrates the difference in the two spectra. In a mode locked laser the overall width is a characteristic of the active medium and the individual components correspond to the longitudinal modes of the resonant cavity. Experimental results utilizing this approach to measure the phase coherence time are reported for a helium neon ring laser that self-pulses or is self mode locked.

To discuss the spectrum of a train of pulses, an ideal pulse shape will be used. The actual shape does not change the results appreciably. That ideal rectangular shape is shown in Figure 2(a) and is represented by rect $\left(\frac{t-t_0}{\tau}\right)$ which has a value of 1 within τ seconds of

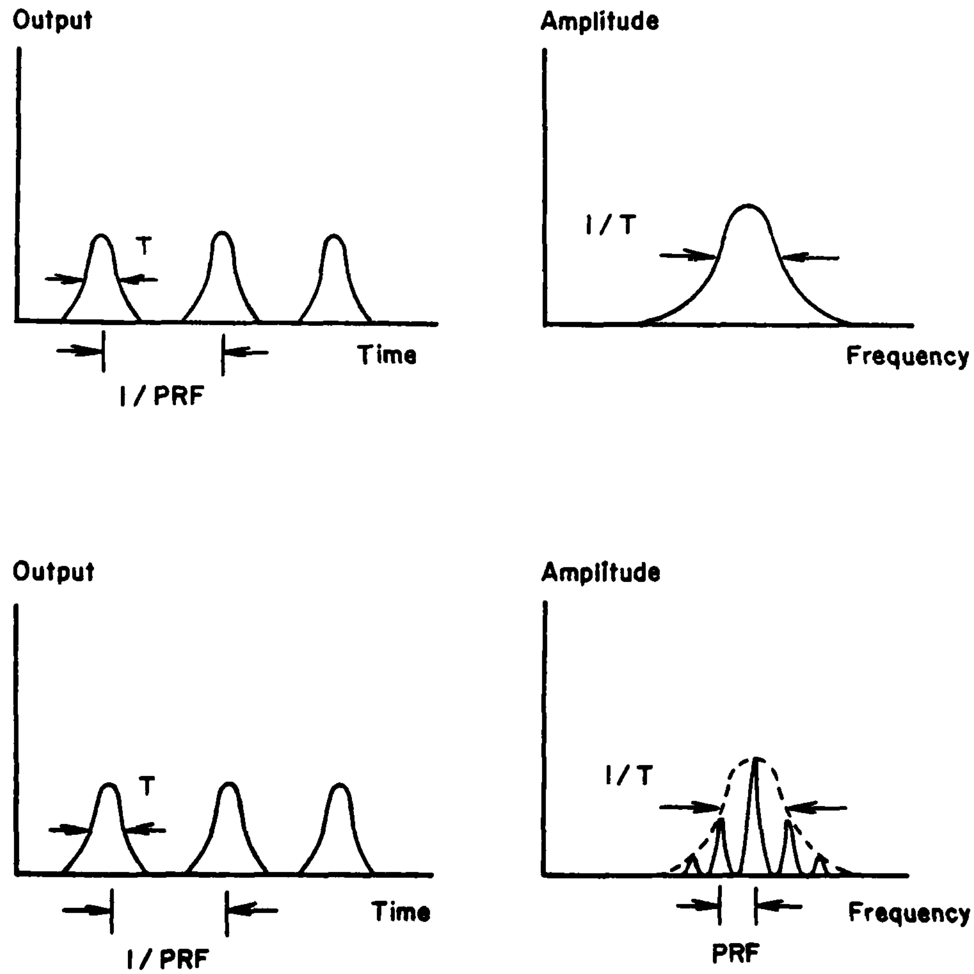

Figure 1. The upper pair of figures illustrate the time domain and frequency domain information for pulses that are not phase coherent. These may be contrasted with the lower pair of figures for pulses that are phase coherent.

t_0 and the value of 0 elsewhere. The spectrum of such a pulse is given by

$$X(f) = \tau \operatorname{sinc} f\tau \; e^{-j\omega t_0} \tag{4}$$

where

$$\operatorname{sinc} f\tau = \frac{\sin \pi f \tau}{\pi f \tau} \tag{5}$$

The full width at half maximum of the central lobe of the spectrum in Eqn. 4 is approximately $1.2/\tau$ indicating the inverse relation between pulse duration and the width in the frequency domain.

A periodic train of rectangular pulses with a period of T_0 or a pulse repetition frequency (PRF) of $f_0 = 1/T_0$ would have the spectrum given by

$$X_n = \frac{\tau}{T_0} \operatorname{sinc}(n f_0 \tau) \; e^{-jn\omega_0 t_0} \tag{6}$$

where $\omega_0 = 2\pi f_0$. This spectrum is shown in Figure 2(b) for positive frequencies. Note that the spectrum consists of equally spaced spikes separated by the PRF with an envelope that is a sinc function whose width is inversely related to τ. Truncation of the periodic train would be represented by multiplication by $\operatorname{rect}\left(\frac{t-t_1}{\tau_1}\right)$ where τ_1 is long compared to τ and also greater than T_0. The spectrum of this truncated train of pulses would then be the convolution of the function shown in Figure 2(b) with the sinc function that is the transform of rect $\left(\frac{t-t_1}{\tau_1}\right)$. Convolution of a function with a spike or impulse function simply yields that function at the location of the spike. Thus, the spectrum of the truncated train of pulses would be as sketched in Figure 2(c). Figure 2(c) demonstrates that the width of the individual spectral components is a measure of the phase coherence time of the train of pulses. This information can be obtained experimentally in an average sense from a scanning Fabry-Perot type spectrum analyzer.

To verify the procedure for measuring phase coherence of a pulse train from its spectrum, an experimental investigation of a self-pulsing helium neon ring laser was conducted. The conditions resulting in pulses were the subject of a paper submitted for publication. The spectrum of the pulses is shown in the paper and is repeated for convenience here as Figure 3. The scale was expanded and the average width of the individual spectral components was approximately 25 MHz. The instrument had a free spectral range of 1.5 GHz and a finesse in excess of 200 indicating a minimum instrumental width of less than 7.5 MHz. Since the measured value was well in the excess of the minimum, the instrument was capable of measuring this aspect of the pulses. A spectral width of 25 MHz indicates a phase coherence time of approximately 50 ns (since the FWHM is $1.2/\tau$). This value is in general agreement with phase coherence times reported

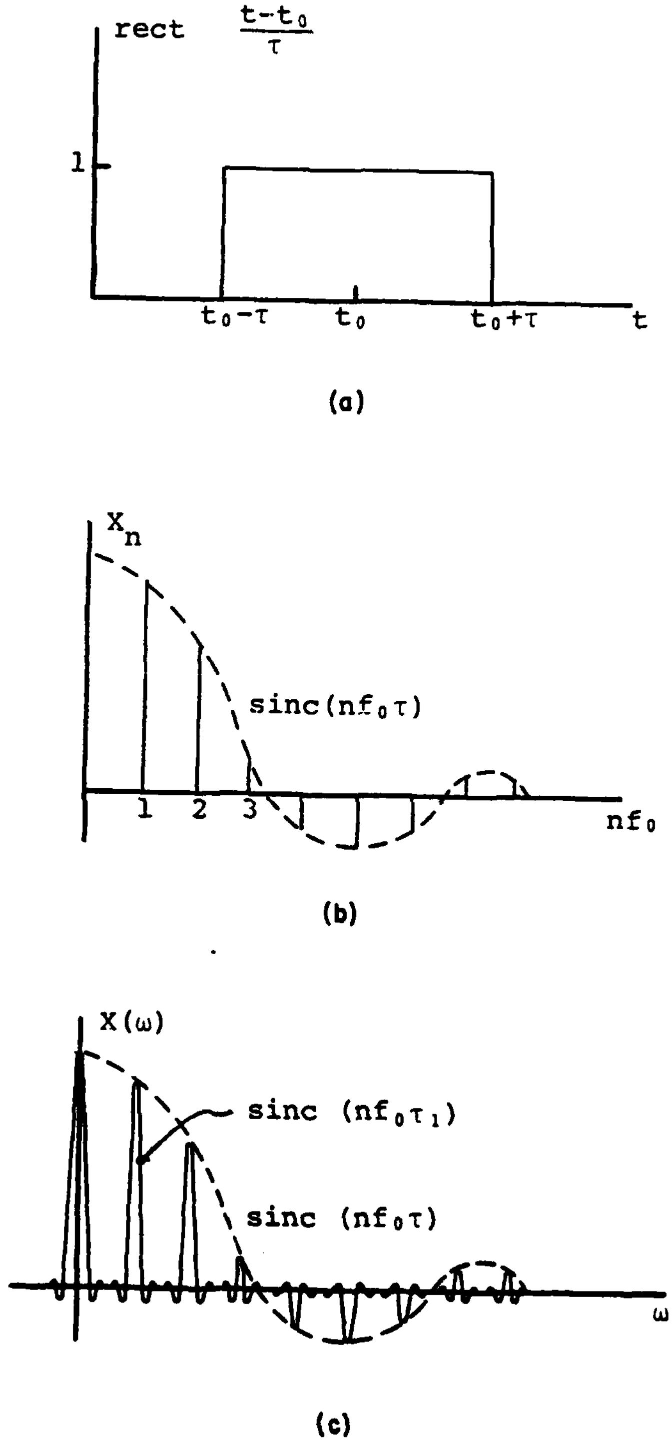

Figure 2. An illustration showing the relationship between the average phase coherence time and the width of spectral components.

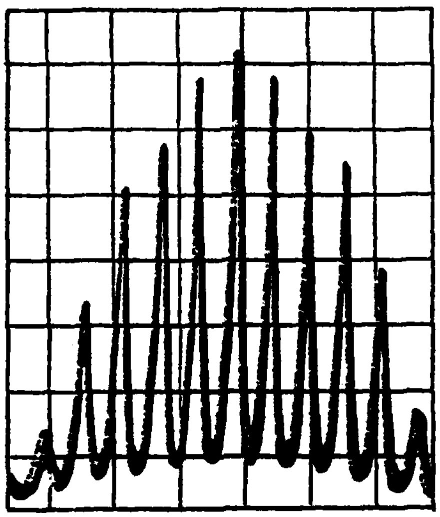

Figure 3. The experimentally measured spectrum of pulses from a self-pulsing helium neon ring laser.

in the literature for helium neon lasers where no particular care has been taken to reduce the influence of disturbing environmental factors.

The use of the spectrum for measuring an average phase coherence time is likely to be limited by the instrumental bandwidth for the spectrum analyzer. Generally, one would like to have an instrument bandwidth no more than one-half of the spectral width to be measured. Using this marginal relationship, the maximum average phase coherence time that can be measured would be

$$\tau_{max} = \frac{1.2}{2\,BW} = 0.6\ \frac{1}{BW} \qquad (7)$$

where BW is the minimum instrument bandwidth. Recall that the minimum instrument bandwidth is the free spectral range divided by the finesse. Thus, a stable laser would necessitate the use of a high finesse spectrum analyzer to measure the average phase coherence time.

Carbon Dioxide Laser Results

Carbon dioxide lasers are good candidates for applications utilizing heterodyne detection because they are good sources of phase coherent radiation. Range doppler laser radar may require hundreds of high power, short phase coherent pulses within a 10 microsecond time interval. A leading candidate for this application is then a mode locked TEA laser. In addition, injection locking is an effective technique for mode locking a high power system and at the same time providing excellent frequency stability or phase coherence. Thus, the results reported in this section are appropriate for an injection locked TEA laser although the analyses can be generalized to other systems. The processes that limit phase coherence are mirror motion and index of refraction changes. Mirror motion can be the result of vibrations and/or thermal effects, either fluctuations or heating. Index of refraction variations arise from electron density fluctuations, molecular and ion density fluctuations and pressure changes due to fluctuations and/or heating.

It is apparent that the factors limiting phase coherence are environmental or laboratory phenomena, such as power supply effects, cooling system effects, and gas supply effects. For example, care must be taken to ensure that the plasma remains stable during laser action to avoid having a time varying load for the power supply. A time varying load would cause current fluctuations and, thus, electron density fluctuations unless the power supply can regulate fast enough to prevent the fluctuations. Various techniques are used to stabilize the plasma. Among these are proper electrode design and supplementary ionization such as ultraviolet ionization. Cooling system effects are principally vibrations of the mirrors forming the resonant cavity. These vibrations can be coupled to the mirrors from cooling water flow irregularities, through acoustic coupling and through convection if fans are used. Gas supply effects must be considered in the design of stable lasers because TEA lasers are usually flowing gas systems even though some work has been reported on sealed TEA lasers [7-8]. Thermal effects are often a significant factor because of the heat generated during the time the TEA laser is on (typically, a TEA laser will be operated in bursts lasting a few microseconds.) This pulsed operation results in a thermal environment that is always changing or transient.

The fact that environmental factors limit frequency stability or phase coherence is readily verified by considering the phase noise that results from spontaneous emission. This emission represents an irreducible fluctuation in the frequency or phase. As discussed in a previous section, this fluctuation manifests itself in the spectrum of the signal as a non-zero width associated with the spectral components. For a continuous signal the full width at half maximum of the spectral component is [9]

$$\Delta\nu_{sp} = \frac{4\pi h\nu}{P}(\Delta\nu_c)^2 \qquad (8)$$

where h is Planck's constant, ν is the optical frequency, P is the power level, and $\Delta\nu_c$ is the linewidth of the resonant cavity. Even for milliwatt power outputs this width is much less than one Hertz indicating that other factors are much more important than spontaneous emission noise.

Thermal effects can cause frequency or phase variations by altering the distance between the mirrors. With mirrors spaced by a homogenous material of uniform cross section, the fluctuation of the laser frequency is [4]

$$\Delta\nu_T = \nu\left(\frac{2kT}{YV}\right)^{1/2} \qquad (9)$$

where k is Boltzmann's constant, T is the temperature, Y is Young's modulus, and V is the volume of the spacer material. The importance of this factor can be evaluated for a given experimental arrangement. A typical value for $\Delta\nu_T$ would be 0.1 Hz for a 10.6 μm CO_2 laser. The fractional change in frequency can be shown to be equal to the fractional change in cavity length. That is,

$$\frac{\Delta\nu}{\nu} = \frac{\Delta L}{L} \qquad (10)$$

Thus, a fluctuation in frequency of 0.1 Hz with a 50 cm cavity length corresponds to a change in cavity length of only about 10^{-14} cm or 10^{-6} Å. It is also apparent that thermal changes would result in cavity length changes much larger than that caused by thermal fluctuations. 10^{-6} per degree is a nominal coefficient of thermal expansion for materials such as invar. Thus, a frequency stability bandwidth of 100 Hz would typically correspond to a temperature change of only 10^{-6}°C. ULE is then recommended for stable laser design since thermal stabilization to 10^{-6}°C is not possible with present designs. Careful attention to experimental details can easily result in improvements of ~ 10^4 in frequency stability or phase coherence over what is achieved in the usual laboratory environment.

Relevant experimental results are found in the work of Lachambre, et al. [1]. They incorporated a low pressure stable gain tube into the same cavity as the TEA section to provide a continuous reference laser beam for stabilization. This hybrid system was not mode locked but the stabilization techniques used provide information for mode locked systems. It was observed that the time rate of change of the phase (or the instantaneous frequency) changed during the microseconds long bursts from the TEA laser. An empirical relation was used to fit a curve to the experimental results for the best frequency obtained by mixing the TEA laser output with a stable low power laser. That relation was

$$\dot{\phi} = \nu_0 + bt^2 \tag{11}$$

where ν_0 is the beat frequency at the beginning, b is a constant adjusted to fit the data, and t is time. b was found to be approximately 0.575 MHz/μs^2. This corresponds to a frequency change of approximately 2.5 MHz during the first 2 μs of output. In terms of spectral widths, this phase change or frequency deviation results in an increase in the widths of the spectral components of from 0.5 to 2.0 MHz FWHM [1]. Lachambre, et al. [1] conclude that the frequency change could be reduced by using a different discharge and electrode configuration to stabilize the index of refraction.

Jacobs, et al. [6], support the conclusion that index of refraction changes dominate the factors affecting phase coherence. Unfortunately, most of the phenomena affecting index of refraction changes are too rapid to allow mechanical servo correction. The index of refraction inside the plasma of the active medium can be expressed as [10]

$$n = 1 - \frac{N_e e^2}{2 m_e \epsilon_0 \omega^2} + 2\pi \sum_m \alpha_m N_m + 2\pi \sum_i \alpha_i N_i \qquad (12)$$

The contribution of the ions is negligible [11] for typical conditions found in TEA lasers. As reported by Jacobs, et al. [6], for a TEA laser Eqn. 12 yields

$$n \approx 1 - 5 \times 10^{-7} + 10^{-4} \qquad (13)$$

for electron density of 10^{13} /cm^3 [11]. Fractional changes then can be written [6]

$$\Delta n = -5 \times 10^{-7} \Delta N_e + 10^{-4} \Delta N_m \tag{14}$$

Eqn. 10 indicates that

$$\frac{\Delta \nu}{\nu} = -\frac{\Delta n}{n} \tag{15}$$

However, the plasma region does not completely fill the space between the mirrors and n is approximately one. Thus, with p being the fraction of the mirror separation containing the plasma, Eqn. 15 yields [6]

$$\frac{\Delta \nu}{\nu} = -p \, \Delta n \tag{16}$$

A reasonable value for p times ν would be 10^{13} Hz for carbon dioxide lasers operating at 10.6 μm. For that case, Eqn. 16 and 14 yield [6]

$$\Delta \nu = 5 \times 10^{6} \Delta N_e - 10^{9} \Delta N_m \tag{17}$$

Thus, a 1% change in pressure would result in a 10 MHz change in frequency and a 1% change in current would result in a 50 KHz change in frequency.

The primary factor casuing changes in pressure is heating, as discussed previously. Two sources of heating are the discharge itself and the losses in the laser action. A detailed analysis of these effects would necessarily require numbers pertaining to a particular laser configuration. Jacobs, et al. [6], report some estimates for their experimental conditions and conclude that their measured frequency change of less than 1 MHz is a reasonable number. The analysis required to assess the pressure change due to heating might proceed as follows. Estimate the energy per unit volume from the discharge that goes into heating. From the specific heat of the gas, the temperature increase can be calculated and this can be used to find the pressure change from the ideal gas law. This disturbance propagates as a shock wave commencing with the current pulse. An additional heating effect takes place as the stored energy in the population inversion starts to heat the plasma when the losses from laser action commence.

Unstable resonators will generally have regions in which changes of the index of refraction do not result in as great a frequency change as stable resonators. The typical Cassegrain resonator will have a peripheral region that is not resonant so that changes in pressure cause a phase change by altering the optical path length. The change of phase in a non-resonant region is given by

$$\Delta\phi = \Delta n \, L \, \frac{2\pi}{\lambda_0} \qquad (18)$$

where λ_0 is the free space wavelength and L is the plasma length. This can be translated into a frequency change by estimating the time over which the change in index of refraction occurs. For the TEA laser example being considered, using Eqn. 14 in Eqn. 18 yields

$$\Delta\phi \approx (-5\times10^{-2}\,\Delta N_e + 10\,\Delta N_m)\,2\pi L \qquad (19)$$

Neglecting electron density fluctuations, a change of 1% in pressure and a 1 meter plasma length results in a phase shift of 0.2π. If this occurs in a microsecond, the frequency shift would be 200 KHz.

It is sometimes instructive to view phase coherence from the point of view of the number of pulses in a train that are in phase. A 1 MHz width of the spectral components would correspond to an average phase coherence time of 1.2 microseconds. With a 20 nanosecond spacing between pulses, approximately 60 consecutive pulses would be phase coherent, on the average. It should be noted that a frequency chirp would require a re-evaluation of the concept of phase coherence. Unless the local oscillator had an identical frequency chirp, the heterodyning would involve a signal with a continuously changing phase. This is a different situation from that analyzed in previous sections of this report.

Active Phase Correction

Certain types of phase shifts or incoherencies in a pulse train could conceivably be corrected by using an active phase correction scheme. That is, the previous discussions have involved passive schemes to reduce environmental effects so as to improve phase coherence. However, these techniques seem to have a limit of around one MHz broadening of spectral components. The next improvement might well result from accepting some lack of phase coherence as inevitable and proceeding with the design of a system to correct the phase after it has left the laser.

The approach would be to condition a phase sensing system during the time the pulse train is phase coherent. The first pulse that is not phase coherent with the previous pulse would then be detected. The phase of this pulse and succeeding pulses might then be corrected to match the phase of the previous pulses. One method for achieving active phase correction is to use a PZT to vary the path length traversed by the pulses. The path length correction or phase correction would take place during the time between pulses.

Some limitations are apparent with such a method. If the phase interruption or incoherency occurred during the pulse, the correction system would have to respond perhaps within one optical period ($\sim 10^{-14}$ sec) rather than between the pulses ($\sim$ 10-20 nanoseconds). This is not possible at present so that this type of incoherency could not be corrected. Also, consideration needs to be given to whether or not feedback can be used in the detection-correction system. This would be desirable so as to drive the phase error to zero. Thus, there are many experimental details that remain for study, but there does not appear to be a fundamental limitation that would prevent active phase correction of certain types of incoherencies. The first step in active phase correction would be to develop an adequate phase detection system.

One possible detection scheme is to use a beam splitter to introduce a delay for part of the beam (see Figure 4). The amount of time delay is carefully adjusted (perhaps using a PZT) to match the interpulse time spacing. The delayed part is recombined with the undelayed part at a photodetector. Thus, the photodetector responds to two pulses overlayed with one another and the output of the photodetector is then phase sensitive. This technique was reported independently by Jacobs, et al. [6].

It is also apparent that there is a need to develop the statistics of phase coherence in pulse trains. To date, only average information is available, but this masks important data regarding such things as maximum and minimum coherence time, standard deviation of coherence time, and whether most phase interruptions occur during the pulse or between the pulses. An experimental measurement of such parameters could be compared to a theoretical analysis modeling the phase disturbing phenomena considered in this report.

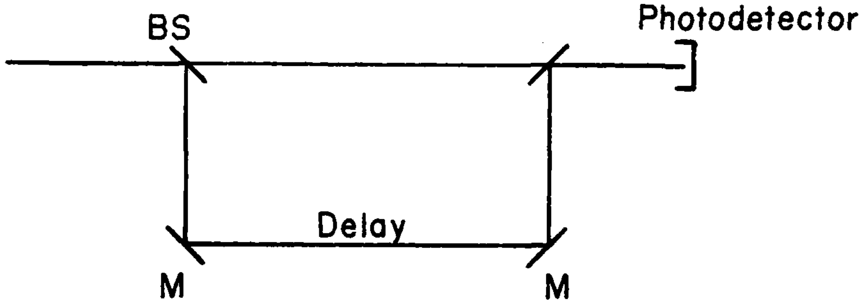

Figure 4. A possible technique for detecting the phase coherence of consecutive or adjacent pulses.

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