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A MAGNETO-OPTICALLY MODULATED CH_3OH LASER FOR FARADAY ROTATION MEASUREMENTS IN TOKAMAKS

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A MAGNETO-OPTICALLY MODULATED CH_3OH LASER FOR FARADAY ROTATION MEASUREMENTS IN TOKAMAKS

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Abstract

Distortion-free intracavity polarization modulation of an optically pumped CH_3OH laser is shown to be viable. The possible use of this modulation technique to make a multichannel Faraday rotation measurement on a Tokamak device is discussed. In addition, the CdTe Faraday modulator employed in this study is shown to have an anomalously large Verdet constant.

Key words: far-infrared lasers, polarization modulation, CdTe Faraday modulator, Verdet constant, Faraday rotation.

Introduction

Recently, the initial observation of intracavity polarization modulation (ICPM) in an optically-pumped far-infrared (FIR) laser has been reported.[1,2] This new technique appears to be a practical and lossless way of modulating the plane of polarization of a FIR laser beam and will be considered in an expanded form in this work.

Briefly, ICPM has been shown to take place in an optically-pumped FIR laser when the pump polarization is modulated by a suitable Faraday device. In a simple laser cavity with no preferred plane of polarization, the FIR output beam polarization is fixed either parallel to or perpendicular to the pump polarization. Therefore, when the pump polarization is modulated (within certain limits of modulation angle and modulation frequency), one expects that the FIR polarization will simply follow the modulation of the pump (without distortion) in a synchronous fashion. See Fig. 1. This last point has been demonstrated experimentally in this work and will be discussed below.

The motivation for this work comes from plasma physics considerations. Recent successful measurements of the poloidal magnetic field in Tokamak devices have employed FIR laser radiation ($\lambda > 300$ μm) which was polarization modulated by passing the beam through an AC Faraday rotation device.[3,4] The active materials in these Faraday devices were ferrites. However, there presently exists a need to extend polarization modulation (PM) techniques to shorter wavelengths than have so far been used. For example, because of plasma birefringence and refraction effects, a poloidal field measurement on the TFTR tokamak presently under construction at Princeton can only be carried out at wavelengths shorter than 150 μm. However, the index of refraction and the absorption coefficient of ferrite material are both prohibitively large for $\lambda < 150$ μm.[5] Hence, ferrite materials cannot be used in the shorter wavelength region. This will be true of most dielectrics at room temperature because of lattice absorption effects present from $\lambda \sim 10$ μm to ~ 200 μm. Therefore, some other PM technique must be employed for wavelengths shorter than 150 μm.

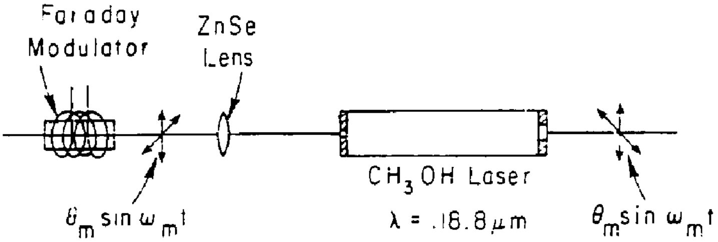


Figure 1. The basic intra-cavity polarization modulation scheme.

In this regard, ICPM appears to be a promising technique and, as is described below, an effort was made to develop a high power optically-pumped CH_3OH laser (λ = 118.8 μm) which employed this modulation technique and which could be shown to be a practical alternative to the ferrite-based technique used at longer wavelengths. To this end, the main thrust of this work is to (1) establish that ICPM can take place without distortion under conditions of modest modulation amplitude (~ 1°) and at modest modulation frequencies (~ 10 kHz), (2) to develop a CH_3OH laser system which could deliver as much power with as large a PM amplitude and as high a frequency as is practical without causing distortion between the pump polarization and the FIR polarization and, (3) to find the best room temperature modulator material available at λ ~ 10.6 μm and to measure its Verdet constant. The first two points will be discussed in the main text while the third point will be treated in an appendix.

Theory

To determine under what conditions of amplitude and frequency ICPM can take place without distortion, we consider a standing electromagnetic wave which is undergoing PM at a frequency ω_m with an amplitude θ_m. This wave, of course, represents the FIR standing wave in the FIR resonator and is assumed, for simplicity, to be immersed in an isotropic gain medium. See Fig. 2.

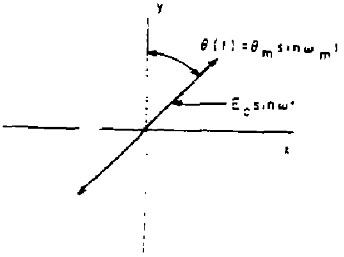


Figure 2. The modulated standing wave in the FIR cavity.

We can write for the instantaneous electric field of this wave:

$$\bar{E} = E_o \sin\omega t \, [\cos\theta(t)\hat{y} - \sin\theta(t)\hat{x}] \qquad (1)$$

where ω is the electromagnetic frequency.

Letting $\theta(t) = \theta_m \sin\omega_m t$ where θ_m and ω_m are the modulation amplitude and modulation frequency, respectively, we have:

$$\bar{E} = E_o \sin\omega t \, [\cos(\theta_m \sin\omega_m t)\hat{y} + \sin(\theta_m \sin\omega_m t)\hat{x}] \; . \qquad (2)$$

Next we substitute the appropriate Bessel function expansion:

$$E = E_o \sin\omega t \, [(J_0(\theta_m) - 2J_2(\theta_m)\cos 2\omega_m t + 2J_4(\theta_m)\cos 4\omega_m t \ldots)\hat{y}$$

$$- (2J_1(\theta_m) \sin\omega_m t - 2J_3(\theta_m)\sin 3\omega_m t + \ldots)\hat{x}] \; . \qquad (3)$$

Taking only the y components and rearranging terms to exhibit "sideband," behavior we have:

$$\begin{aligned} E_y = {} & E_o J_0(\theta_m)\sin\omega t \\ & + E_o J_2(\theta_m)[\sin(\omega + 2\omega_m)t - \sin(\omega - 2\omega_m)t] \\ & + E_o J_4(\theta_m)[\sin(\omega + 4\omega_m)t - \sin(\omega - 4\omega_m)t] \; . \qquad (4) \\ & + \ldots \end{aligned}$$

Similiarly we have for the x component:

$$\begin{aligned} E_x = {} & E_o J_1(\theta_m)[\cos(\omega - \omega_m)t - \cos(\omega + \omega_m)t] \\ & + E_o J_3(\theta_m)[\cos(\omega - 3\omega_m)t - \cos(\omega - 3\omega_m)t] \qquad (5) \\ & + \ldots \end{aligned}$$

Having thus characterized the resonator electric field in terms of its sidebands we can now see that in order for ICPM to take place without distortion, all the sidebands of both E_x and E_y must fit well within both the gain bandwidth of the lasing medium and the cold cavity bandwidth of the resonator supporting the standing wave. It is assumed that the cavity is tuned to the line center of the lasing medium so that frequency-pulling effects need not be considered. It is also assumed that only a single linearly polarized (say EH_{11}) cavity mode is on "speaking terms" with the gain curve and that no transverse modes are present. This condition is rather easily realized in most FIR lasers. This situation is summarized in Fig. 3.

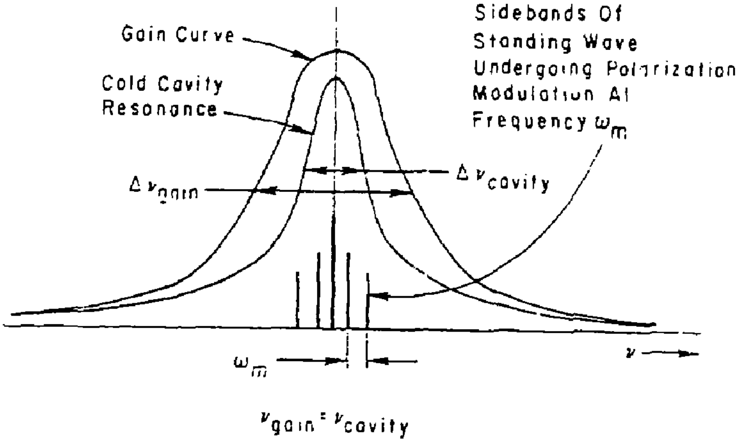


Figure 3. The gain curve, cold cavity resonance and sideband structure of a typical magneto-optically modulated FIR laser system.

For a typical longitudinally pumped FIR laser, the bandwidth of <u>both</u> the cold cavity and the FIR lasing medium are on the order of 1-10 MHz.[5] This, then, respresents the largest possible modulation frequency. However, because the Verdet constant of available Faraday modulation materials is small ($\lesssim 2.5 \times 10^{-1}$ deg/KG cm) one is limited by practical considerations to rather modest modulation angles (θ_m << 1 rad, say 1-5 degrees) and rather modest modulation frequencies (< 100 kHz). Under these circumstances we can neglect several terms in Eqs. (4) and (5). Specifically we can write:

$J_o >> J_2 >> J_4 >> \ldots$

and for $\theta_m << 1$ (6)

$J_1 >> J_3 >> \ldots$

Therefore we re-write Eqs. (4) and (5) as:

$$E_y = E_o J_o(\theta_m) \sin \omega t \tag{7}$$

and

$$E_x = E_o J_1(\theta_m) [\cos(\omega - \omega_m)t - \cos(\omega + \omega_m)t] \tag{8}$$

Hence, it can be seen that under conditions of small modulation amplitude, only the x component of the FIR resonator electric field contains any significant sideband components and in fact contains only the first sideband. Therefore, for $\theta_m << 1$ and $\omega_m << 1$-10 MHz, one can expect that ICPM will take place without distortion. These are the conditions under which the measurements described below were performed.

Experiment

If PM of an electromagnetic wave takes place at a frequency ω_m with an amplitude θ_m, then that PM can be characterized by allowing the beam in question to pass through a polarizer oriented at 45° to the plane of polarization of the incoming wave. The signal that results from allowing the transmitted beam to fall on a detector is then given by

$$V = P_o \theta_m \sin \omega_m t \tag{9}$$

where $\omega_m << \omega$ (the electromagnetic frequency) and P_o is the power transmitted through the polarizer.

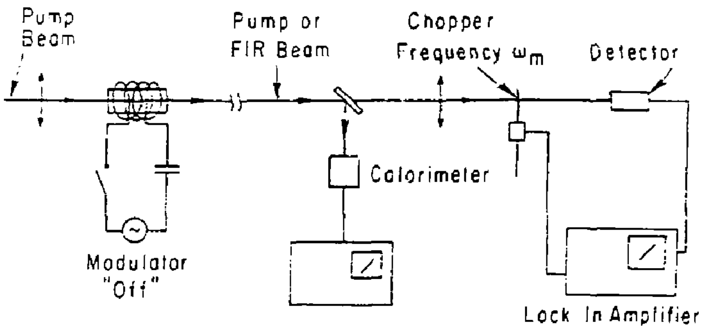
With this fact in mind the experimental apparatus shown in Fig. 4 was established to demonstrate that PM of the FIR output of a CH_3OH laser (λ = 118.8 μm) can take place without distortion (i.e., that the modulation amplitudes and frequencies of the pump and FIR are equal).

The Faraday rotation device consisted of a 25 mm diameter x 75mm solenoid on which were wound 600 turns of #22 copper wire and at tank resonance drew as much as 6 amperes (peak) from a 75 watt power amplifier. Under these conditions the coil delivered a 0.4 kG central field at a frequency as high as 8.7 kHz. The active material consisted of a 12.5 x 12.5 x 50.8 mm ingot of polycrystalline CdTe which was polished and antireflection coated for maximum transmission at 9.6-10.6μm. The choice of CdTe as a modulator material will be discussed in a later section. The CO_2 laser and FIR resonator were of standard design and are described elsewhere.[1]

The apparatus shown in Fig. 4a was established in order to calibrate the detector response. The discussion that follows applies to the measurement of both the pump and the FIR modulation amplitude since the procedure employed to measure these quantities was identical (only the detectors and beamsplitters were different). To calibrate the detector in question, a detector signal was generated with a chopper operating at a frequency ω_m (with the Faraday modulator turned off). A relative measurement of the power in the beam was provided by splitting off a portion of the beam on to a Scientech 361 calorimeter. The detector response was then calibrated against the calorimeter reading. Next, the chopper was removed and a polarizer oriented at 45° to the plane of the beam polarization was inserted in the beam (see Fig. 4b). The modulator was next activated at a tank current of 4.0 amperes. The detector signal which developed due to the polarization modulation of the beam ($v = P_o \delta_m \sin \omega_m t$) was next compared against the power reading of the calorimeter. By using the data generated in configuration b and correcting this data for the detector response as measured in configuration a, a value for δ_m could then be determined. (Care was taken to correct for the square wave nature of the data generated using the chopper as against the sine wave nature of the observed PM).

Also, by measuring δ_m in this way for the pump beam and by measuring the current-to-field conversion coefficient of the Faraday coil employed, the bulk Verdet

(a) DETECTOR CALIBRATION PROCEDURE



(b) MODULATION ANGLE MEASUREMENT

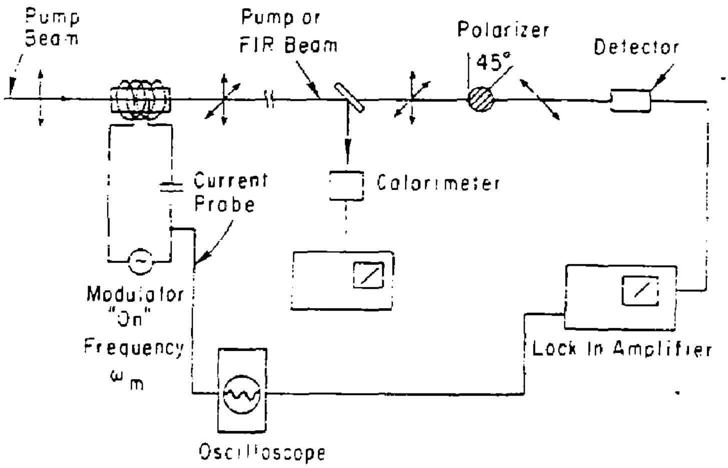


Figure 4. The experimental configuration used to characterize both the pump and the FIR polarization modulation. The same configuration was used to measure the bulk Verdet constant of the CdTe modulator employed.

constant of the CdTe Faraday specimen was determined. The results of this measurement will be discussed in the appendix.

Results

As described above, the modulation amplitude of both the pump and the FIR polarizations were measured independently in the ~ 0.3-0.4 degree range at several frequencies between 85 Hz and 10 kHz. In all cases these measurements indicated that in this amplitude range the FIR modulation amplitude was equal to that of the pump (within experimental errors of ± 10%). This result was anticipated in the theory section of this work.

Having established that ICPM can take place without distortion an effort was next made to develop a prototype laser system which could be used to make a multichannel measurement of Faraday rotation on a tokamak device. Emphasis was, of course, placed on delivering as much FIR power with as large a modulation angle and as high a modulation frequency as possible. The results of that work are summarized in Table 1.

It should be noted that the pump-to-FIR power conversion efficiency of this modulated laser system compares very well to the most efficient CH_3OH laser system reported to date.[7]

Table I

ICPM RESULTS TO DATE

FIR WAVELENGTH	118.8μm
PUMP POWER	~ 20W
PUMP θ_M	0.5 deg
FIR POWER	125mW
FIR θ_M	0.5 deg
MODULATOR FREQUENCY	8.7 kHz
MODULATOR FIELD	~ 0.4 kG

Conclusion

The modulation parameters as well as FIR power generated by this prototype system compare reasonably well to those discussed in the Faraday rotation feasibility study of Kunz.[4] Hence, on that basis it can be said that with the proper choice of detectors (say a Ge:Ga photoconductor, NEP = 10^{-11} -10^{-12} W/Hz$^{1/2}$) a multichannel Faraday rotation measurement could be performed using the system described above. Therefore, ICPM can be a practical alternative to ferrite-based modulation techniques.

In addition, several improvements to the prototype system described above are possible. For example, by passing the pump beam through the modulator several times (say n times) an n-fold enhancement of the modulation angle δ_m is possible, because the sense of Faraday rotation does <u>not</u> reverse with a change in the direction of propagation of the beam in question. The absorption coefficient of CdTe is so small (< 0.001 cm^{-1}) that several passes through the crystal will not decrease the pump power significantly.

Appendix: Modulator Materials

A literature search was made in an effort to find the best material available which had a resonably large Verdet constant, had low enough absorption to be able to handle high CW pump power densities (~ 100 W/cm^2), and could be used at room temperature.

Shown in Table 2 are the results of that literature search as well as the results of our measurements on CdTe. As can be seen, the most promising modulator materials are the cubic semiconductors.

As can also be seen in Table 2, <u>intrinsic</u> CdTe has a very large figure of merit (V/α) and was therefore chosen as the modulator material employed in this study. However, it should be noted that the bulk Verdet constant of the sample of <u>nominally</u> <u>intrinsic</u> CdTe employed in this study was measured to be roughly one order of magnitude larger than was expected in an intrinsic material, while the absorption of the sample was essentially equal to that of an intrinsic sample. This resulted in an extremely large figure of merit for the sample employed.

Table II: Comparison of Room Temperature Modulators at $\lambda = 10.6\mu m$

Modulator Material	V deg/KG-cm	α cm^{-1}	V/α deg/KG	Comments	Reference
CdTe Intrinsic Crystalline	0.0339	0.0005	68		8
CdTe Doped (n) Polycrystalline	0.3	<0.001	200-300	Numbers Represent our modulator	
ZnSe Intrinsic Polycrystalline	0.015	<0.005	>3	V calculated from Energy gap	9
ZnSe Doped (n) Polycrystalline	-	-		V is seen enhanced by doping	9
Ge Intrinsic Crystalline	0.0827	0.0165	5	Thermal runaway a problem	8
GaAs Doped Crystalline	0.0499	0.025	1.6		8
$Hg_{1-x}Cd_xTe$ Doped (n) Polycrystalline	0.55	<0.5	>1.2		10

A possible explanation for the enhanced Verdet constant of the sample employed could be an excess of indium doping. The Verdet constant of cubic semiconductors arises from both the interband (or bound electron) and the intraband (free electron) contributions and can in general be written as:

$$V(\lambda) = \underbrace{a/\lambda^2}_{\text{interband term}} - \underbrace{N_e b\lambda^2}_{\text{intraband term}} \qquad (10)$$

where a and b are material constants, N_e is the free carrier concentration and λ is the electromagnetic wavelength in question. Marple has shown that a very large enhancement of the Verdet constant in CdTe can be achieved with indium doping (or n doping in general) when N_e is made so large that the intraband term dominates the interband term.[11] The sample of CdTe used in this study was grown (commercially) with an excess of indium but the resulting doping level is unknown.[12] Clearly, the possibility exists that with a judicious choice of doping the figure of merit of CdTe could be optimized. A further advantage of using a cubic semiconductor as a modulator material is that the use of polycrystalline samples is permitted because the Verdet constant in cubic materials is isotropic. The use of polycrystalline material greatly reduces the cost involved and greatly increases the availability of large modulator samples.

Shown in Fig. 5 is the observed wavelength dependence of the Verdet constant of the CdTe sample employed in this work.

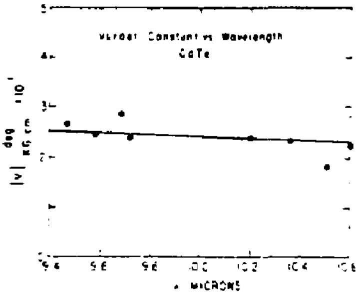


Figure 5

Acknowledgments

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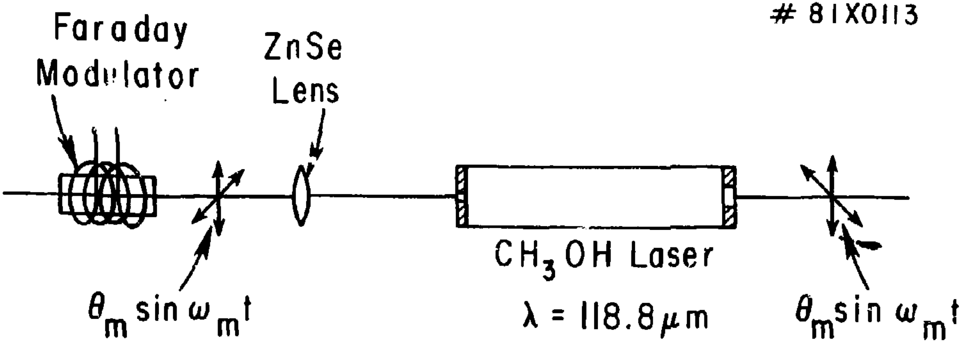

Fig. 1 The basic intra-cavity polarization modulation scheme.

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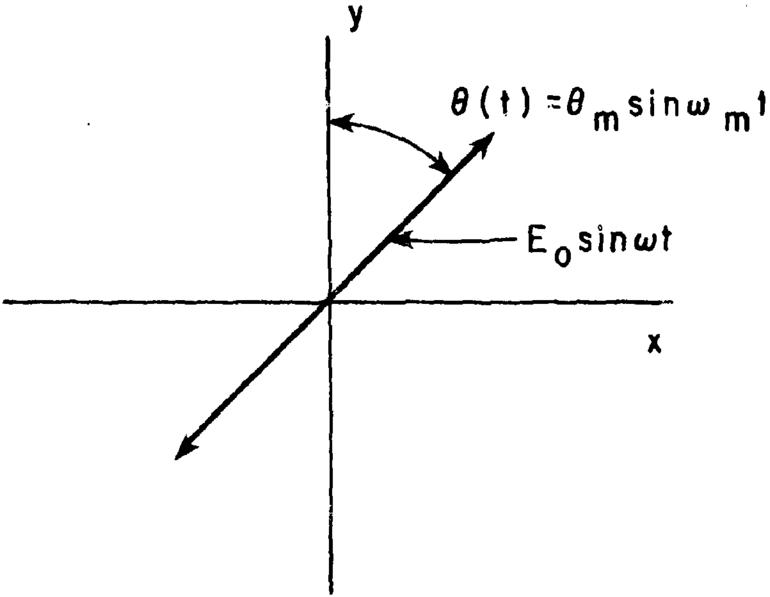

Fig. 2 The modulated standing wave in the FIR cavity.

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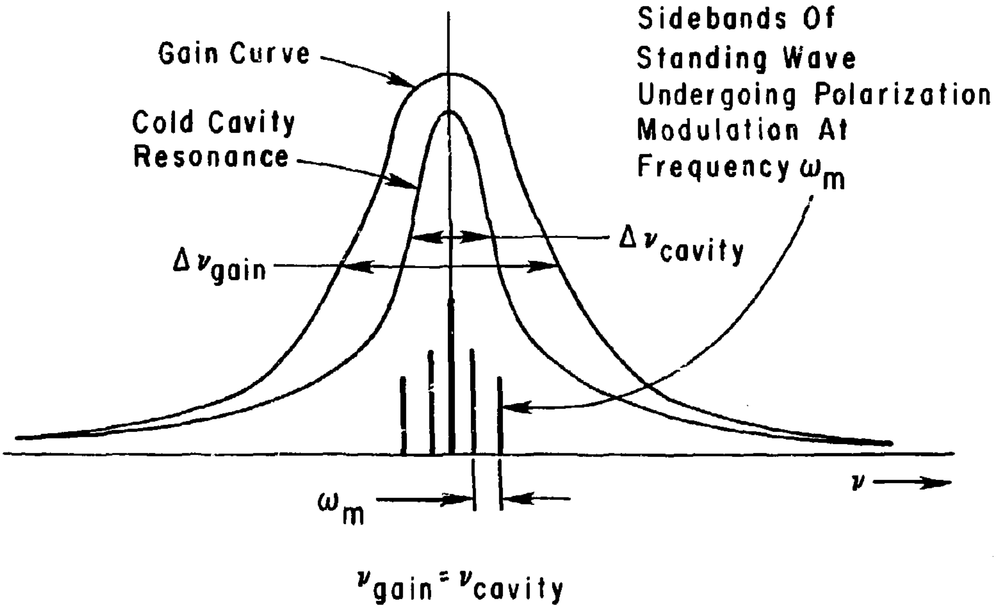

Fig. 3 The gain curve, cold cavity resonance and sideband structure of a typical magneto-optically modulated FIR laser system.

(a) DETECTOR CALIBRATION PROCEDURE

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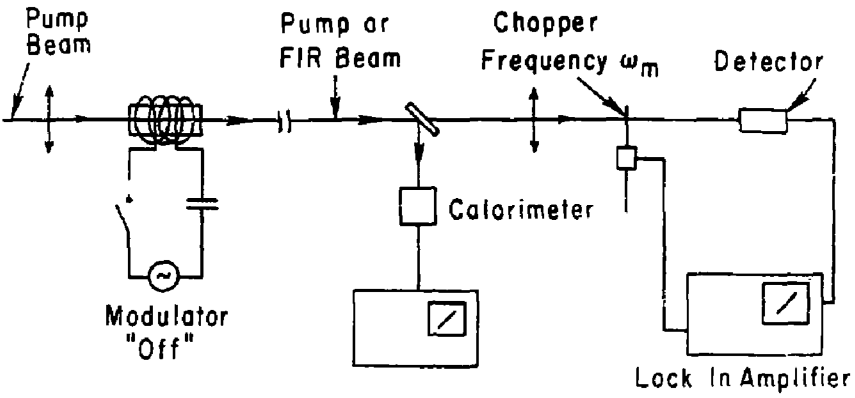

(b) MODULATION ANGLE MEASUREMENT

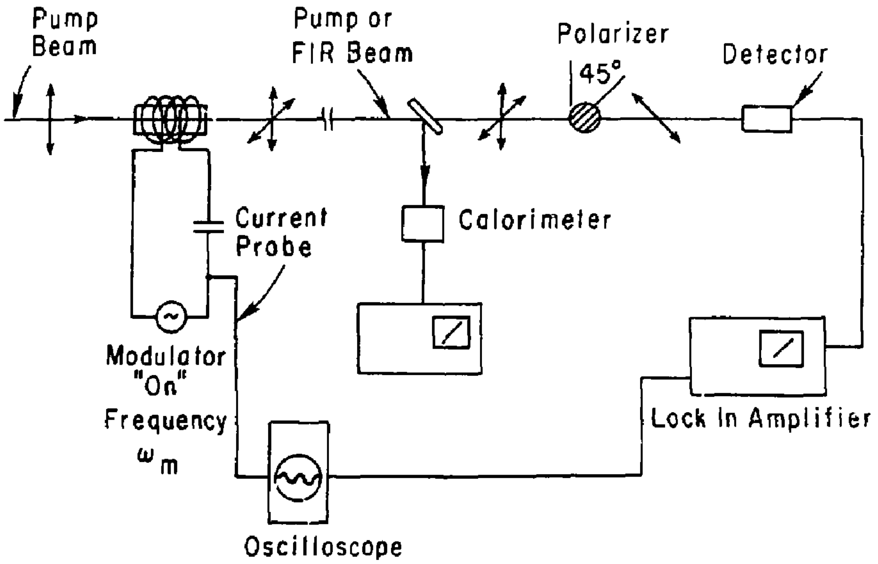

Fig. 4 The experimental configuration used to characterize both the pump and the FIR polarization modulation. The same configuration was used to measure the bulk Verdet constant of the CdTe modulator employed.

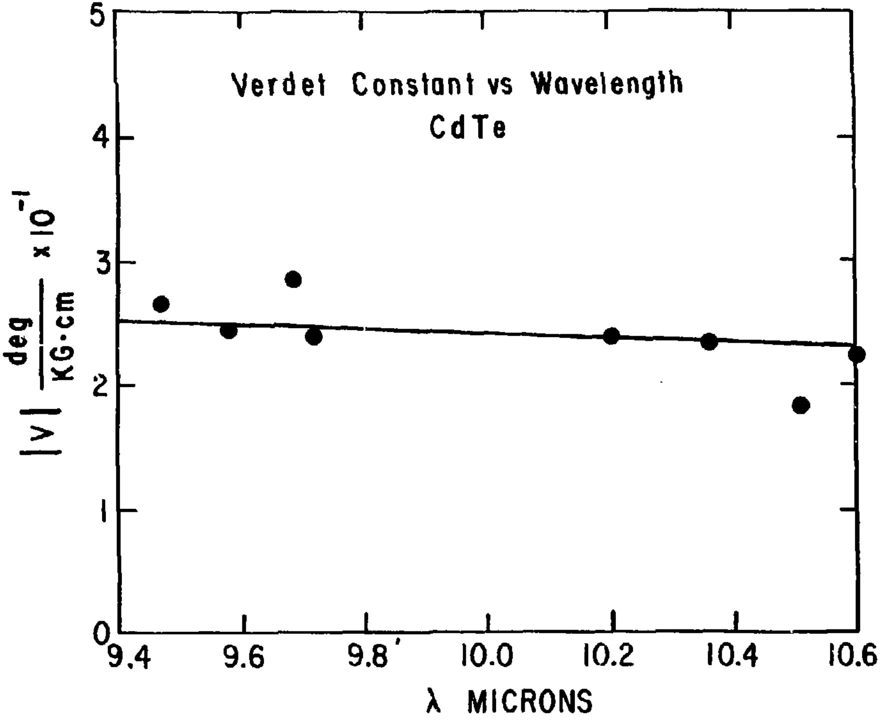

Fig. 5 The wavelength dependence of the Verdet constant for the CdTe sample employed in this work.