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AN OPTICAL HETERODYNE DENSITOMETER

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Abstract -- We are developing an optical heterodyne densitometer with the potential to measure optical density over an unprecedented dynamic range with high accuracy and high sensitivity. This device uses a Mach-Zender interferometer configuration with heterodyne detection to make direct comparisons between optical and RF attenuators. We expect to attain measurements of filter transmittance down to 10^{-12} with better than 1% uncertainty. In addition we intend to extend this technique to the problem of measuring low level of scattering of light from both reflective and transmissive optics.

I Introduction

We have developed a system to measure optical density over an unprecedented dynamic range with high accuracy and high sensitivity. Using the ultra-sensitive technique of optical heterodyne detection, we have been able to measure optical attenuations of 10^7, 10^{10}, and 10^{12} at 633 nm with standard deviations of 0.5%, 2.5% and 20% respectively.

Optical heterodyne detection[1] uses a strong reference laser beam, or local oscillator, to amplify very weak signals above the noise inherent in the detector. In this way, the shot noise of the strong reference beam can be made to dominate the measurement rather than the detector noise. Our setup (Fig. 1) uses a laser split equally into two beams, one of which is sent through the filter to be measured and then frequency shifted by an acousto-optic modulator. The two beams are then recombined and sent to a detector which sees a beat signal at the difference frequency. The amplitude of the beat signal is proportional to the square root of the filter transmittance. It is this square root dependance that, in part, gives heterodyne detection its increased dynamic range over ordinary densitometry measurements that depend linearly on transmittance.

This method makes possible measurements that cannot be made any other way, the most obvious being accurate single frequency measurements of high attenuation absorbing glass filters. Also, since this method is not limited to a specific frequency, a tunable laser source can be used to measure the transmission profile of an interference/blocking filter far out into the wings. In addition, very low level scattering by optical components can be quantified.

II Theory

Heterodyne detection, described as follows, uses a light wave of one frequency to detect a signal at a second slightly different frequency. The photocurrent i(t) from a photodetector is proportional to the light

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intensity $I(t)$ incident on the device at time t. Intensity is the square of the sum of the electric fields of the two beams E_0 and E_1. So if two beams are combined, $I(t)=|E_0(t) + E_1(t)|^2$. If the two beams have different optical frequencies, ω and $\omega+\Delta$, then when $I(t)$ is averaged over many optical cycles, a cross term at the difference frequency Δ will arise in addition to a constant term. This term at the difference frequency is proportional to E_0E_1 or $(I_0I_1)^{1/2}$, where I_0 and I_1 are the intensities of the two individual beams. The square of the amplitude of the beat signal is proportional to the intensity of each beam. One can see that if the two beams differ in intensity, the more intense beam effectively amplifies the signal due to the weak beam.

When averaged over the detector area, the signal current from the detector may be written as:

$$i(t) = K [1 + 2(TP_1/P_0)^{1/2}\cos(\Delta t)]$$

where $K = P_0e\eta/\hbar\omega$, P_0 and P_1 are the laser powers in the two beams, e is the electron charge, η is the detector quantum efficiency, $\hbar$ is Planck's constant over 2π, ω is the optical angular frequency, Δ is the difference frequency, and T is the transmittance (assumed to be <<1) of an optical filter inserted into the P_1 beam path. Thus, the optical attenuation is found by taking the square of the ratio of the beat signal with and without the filter inserted.

An important point to note about this technique is that extreme requirements on detector linearity are not necessary. This results because the unattenuated beam effectively biases the photodetector. One can see that as the filter transmittance changes from full transmission to total attenuation the intensity on the detector changes by only a factor of two.

The sensitivity of this technique may be defined as that transmittance that will produce a signal amplitude just equal to the noise in the system (ie. signal/noise = 1). If the unattenuated laser beam is powerful enough, its shot noise will dominate the detector noise, so the noise current squared may be written as:

$$<i_n^2> = 2P_0e^2\eta B/\hbar\omega,$$

where B is the bandwidth of the measurement. The sensitivity is found by setting this equal to the heterodyne signal current squared written as:

$$<i_s^2> = 2e^2\eta^2TP_0P_1/(\hbar\omega)^2$$

and solving for T. This gives a transmittance sensitivity $T=\hbar\omega B/\eta P_1$. For a HeNe laser power of 1 mw in each beam and a 1 Hz bandwidth this minimum detectable transmittance is 3×10^{-16}.

III Experimental Technique

Our optical setup is based on a simple Mach-Zender interferometer where a 1 mw HeNe laser beam is split into two beams and subsequently recombined. The filter of interest is placed in one of the beams. The beam transmitted by the filter is then frequency shifted by an acousto-optic modulator (AOM) driven at 36 MHz. The unattenuated beam and the attenuated and frequency shifted beam are recombined by a beam splitter and focused onto a detector/amplifier. The detector produces a DC signal plus the AC component at the difference frequency of the two beams. The amplitude of the beat signal depends on the intensity of the recombined beam and thereby on the transmittance of the filter.

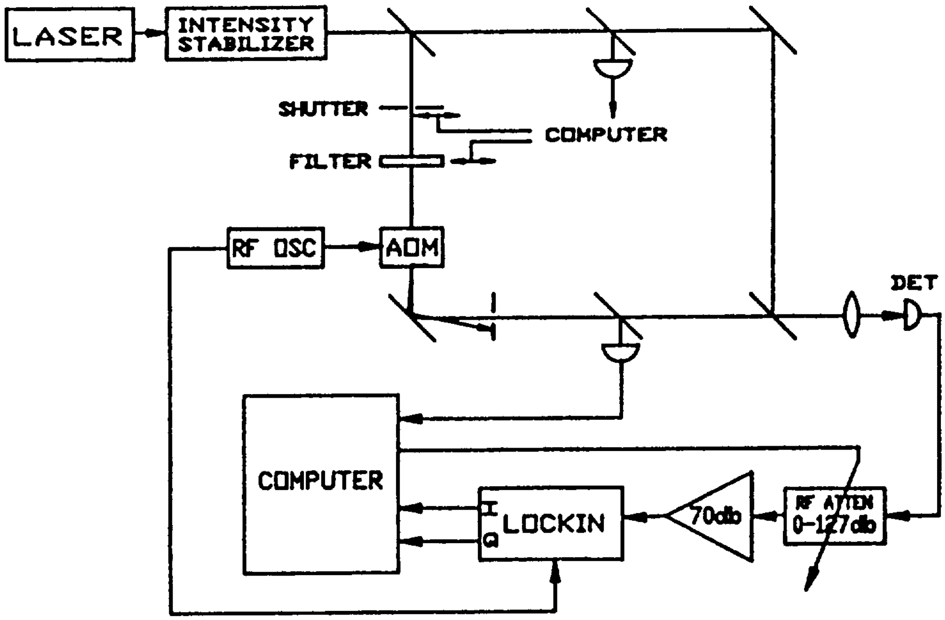

Figure 1 Schematic of Experiment

The AC output of the detector/amplifier is put into a computer controlled 0-127 db RF attenuator followed by two 35 db gain RF amplifiers. The signal along with the AOM drive frequency is then fed into a 50 MHz lock-in amplifier. This produces two DC signals, one proportional to the beat signal in phase with the drive frequency and the other proportional to the signal in phase with the drive frequency shifted by 90 degrees. These inphase and quadrature signals are recorded by the computer which calculates the magnitude of the beat signal.

When the filter is removed from the optical path, the RF attenuator is increased to maintain a nearly constant signal at the lock-in. By alternately recording the beat signal (including the RF attenuation) with the filter in and out, any problems due to slow changes of the RF gain are eliminated. The computer also monitors the laser power and the power of the frequency shifted light exiting the AOM to normalize the beat signal. An optical shutter placed in the frequency shifted arm and controlled by the computer is used to zero the electronics.

This precise arrangement of components was chosen to minimize ordinarily small effects that become important at our high detection sensitivities. We found that the exit surface of the AOM backscattered light at the 10^{-9} level. This produced a beat signal even with the frequency shifted beam blocked, indicating that light backscattered by the output surface of the AOM reached the laser and was reflected into the unshifted beam. To prevent this, the test filter was placed upstream of the AOM so that the backscattered and frequency shifted light is reduced twice by the filter attenuation. Several measures are taken to make the optical phase difference of the two beam paths stable to allow for very narrow bandwidth settings on the lock-in amplifier, and thus reduce the noise. The optical apparatus is enclosed in a box to reduce air turbulence, and the optical table is placed on vibration isolation legs.

Measurements are typically made with 1 s integration times on the outputs of the lock-in and the laser power monitors. A 10 second wait time is used to allow for these signals to settle after changing the shutter or filter position. These delays and the time to reposition the filter (currently via a very slow translator) result in a single measurement taking about 1.5 minutes.

IV Results

Our initial tests were made to characterize the noise and drifts associated with the technique. We found that we could make measurements with 1.5% standard deviation of individual measurements once the interferometer had stabilized. This was accomplished only after correcting for a systematic error of 10% in the lock-in response varying with input phase angle. This correction was able to reduce this problem to approximately 1%. We hope to reduce this further by designing and constructing our own lock-in.

We have made initial tests of the dynamic range and found that measurements of attenuations as great as 10^{-12} could be made with a standard deviation of 20% between individual measurements. This implies a sensitivity in the 10^{-13} range, leaving 3 orders of magnitude, before running up against the theoretical limit using our current experimental parameters.

While most of our initial tests were made using a frequency stabilized HeNe laser, we have successfully run a test using a multimode Ar^+ pumped dye laser, demonstrating the tunability of the technique.

V Conclusion

Our tests thus far have succeeded in demonstrating the extraordinary dynamic range and sensitivity of heterodyne measurement of optical density. This range far exceeds the capabilities of the ordinary attenuation measurements presently in use at NBS. Since the current measurements are not at the fundamental limits of the technique, further work should allow us to push the sensitivity at least an order of magnitude better.

Planned improvements to this system include construction of new lock-in amplifier to reduce systematic errors with respect to phase angle to below the current 1% level. We intend to shift our beat frequency to 30 MHz, where RF attenuators can be calibrated by an available service at NBS in Boulder. This will allow us to complete the traceability of our optical measurements to high precision RF electrical standards and to produce accurate, absolute optical standards. When this is done, we will compare our heterodyne measurements to conventional measurements where the dynamic ranges overlap. In addition, tests will be done to verify the linearity of our technique. Work is also underway to extend this technique to the infrared using a CO_2 laser at 10.6μm.

We intend to measure transmittance versus angle to allow the total transmittance of a filter to be measured. In addition, this will enable us to characterize the distortion of the transmitted wavefront. Another application where this high dynamic range technique should prove useful is in measuring the low angle scattering of both transmissive and reflective optics. This should be particularly useful in the case of the low scatter super-polished mirrors now becoming available.

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1. R.W. Boyd, Radiometry and the Detection of Optical Radiation, p. 195, John Wiley & Sons, New York, 1983.

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