Laser diode coherence length variation with drive current: a tool for dispersion measurements

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ABSTRACT

A visible light (670nm) laser diode was used as a variable coherence length source to measure dispersion characteristics in single-mode fibers. The diode's spectral width, measured against increasing drive current, was found to change from about 16 nanometers to less than 0.2 nanometer. The corresponding change in coherence length is from about 25μm to 2.5mm.

1. INTRODUCTION

This work is part of an ongoing effort to demonstrate the practicality of fiber-based long baseline optical interferometers. Such interferometers would accomplish high spatial resolution images of distant objects by two (or more) widely separated receivers. The signals from these subapertures are carried by optical fibers and interferometrically recombined to obtain phase and amplitude information from the target. This process demands careful (small fractions of a wavelength) control over the effective path length of each of the interferometer arms. We used the variable coherence length, visible light laser diode to measure the relative length mismatch between two long (60m) sections of single-mode optical fiber, and to obtain white light fringes through a two-arm, 60 meter fiber interferometer. This paper discusses experimental procedures and the spectral properties of the diodes used in these experiments.

2. NEED FOR A TUNABLE COHERENCE-LENGTH SOURCE

As shown in Fig. 1, the fiber interferometer can be illuminated with light selected from one of three sources. The laser diode fills the void between the long coherence length helium-neon (HeNe) laser and the short coherence length arc lamp source. The angular alignment of the interferometer is best accomplished using the HeNe as the source, as it provides high signal levels through the single-mode fiber. The goal of this sequence of experiments was to obtain white light fringes (i.e., fringes from the arc lamp source) through the 60 meter fiber links. The fibers were reported to be equi-length to within a millimeter.

Based upon this assumption, and an assumption that the optical pathlength of the fibers would closely match their physical lengths, we attempted to match the air path segments of the setup to within a millimeter, and find the arc lamp fringes by scanning through nominally two millimeters of potential length mismatch. Attempts at doing so failed, leading us to suspect the optical lengths of the two fiber sections did not closely follow the fibers' physical lengths. Finding the HeNe fringes became trivial, but because the coherence length of that source is literally meters long, it could not be used to narrow the search in pathlength space. The ideal source would have a coherence length tunable from near that of the HeNe (long enough to easily find the fringe packet) to nearly as short as that of the arc lamp source. Using such a source, the length of one of the interferometer arms could then be adjusted to maintain maximum fringe contrast while decreasing the coherence length of the source. Finally, the two arms would be matched to within a few tens of micrometers, corresponding to the coherence length of the arc lamp source. It

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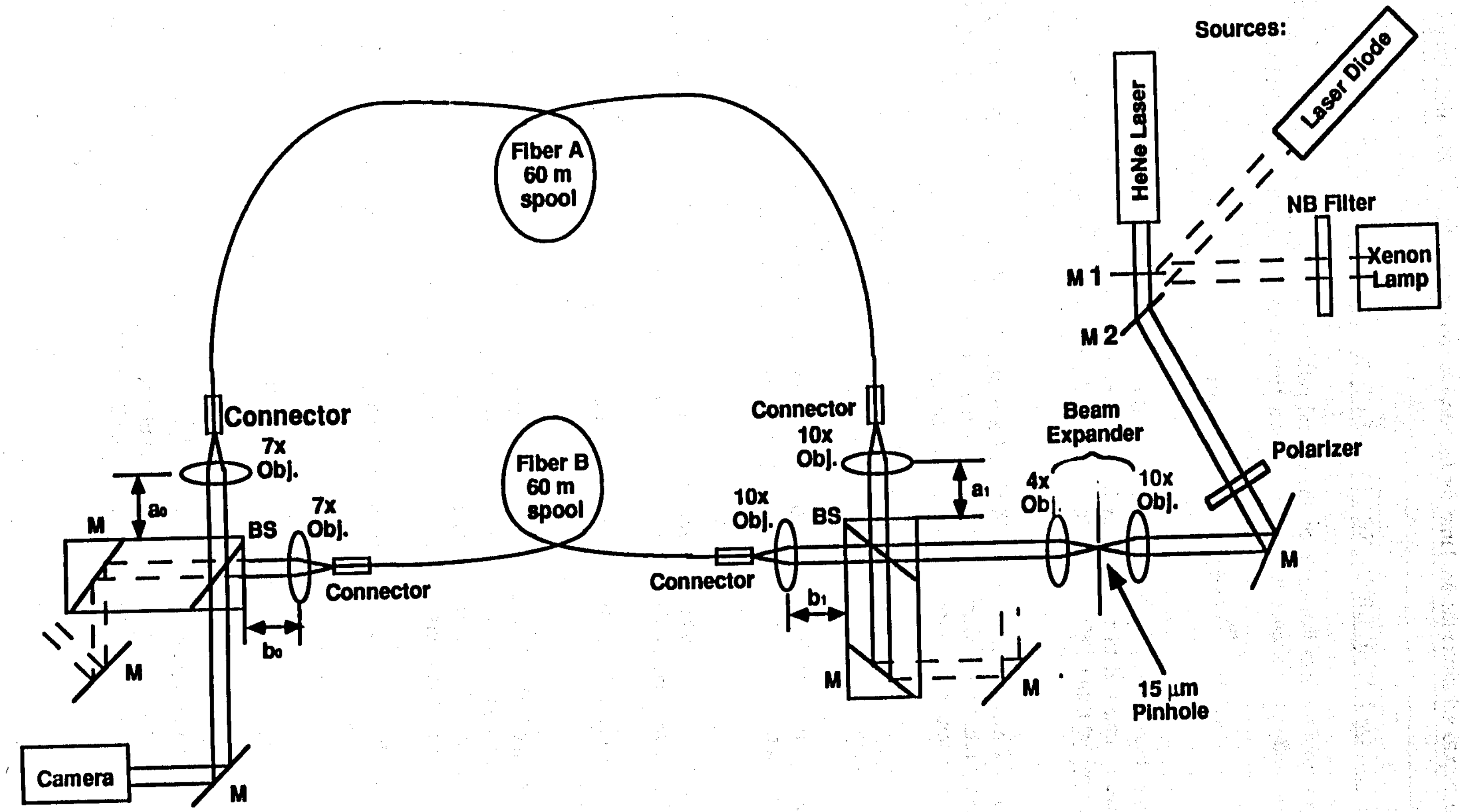

Fig. 1. Schematic of fiber optic interferometer.

would then be a simple step to substitute the arc lamp for the tunable source and obtain white light fringes through the interferometer.

3. USE OF LASER DIODE TO MATCH OPTICAL PATH LENGTHS

In order to obtain fringes from the broadband source, the optical path lengths of the two interferometer arms must be matched to within the source's coherence length, which for a 10nm-wide source centered at 656nm is:

$$1_c = \frac{\lambda^2}{\Delta\lambda} = 43\mu m$$

This is difficult since this close match must be obtained over paths longer than 60m, including the spools of fiber, which (although supposedly matched to within 1mm in length) may possess slight refractive index differences resulting in much greater optical path (OPD) mismatch. Balancing the paths often becomes a difficult trial-and-error search.

A more systematic approach was developed here. We used a 675nm laser diode (Toshiba TOLD 9200) whose coherence length (inversely related to spectral width) can be varied in a quasi-continuous manner by changing its dc drive current and, correspondingly, its stimulated emission gain.

1. Start with maximum drive current to the diode (approximately 61mA). This gives the narrowest spectrum for a course path adjustment. Find fringes and adjust one path for maximum fringe contrast.

2. Reduce drive current in steps (near the lasing threshold), adjusting path length for maximum fringe contrast in each step. For intermediate currents, multiple fringe envelopes will be found; lock on to the one with the maximum contrast.

3. Continue reducing the drive current until the laser diode is clearly below threshold (less than 40mA) and the spectrum is widening. Continue to adjust the path for maximum fringe contrast.

4. Replace the laser diode source with the 10nm filtered xenon source. White light fringes should be obtained with only slight path adjustment.

A key element of this technique is the changing laser diode spectrum versus drive current. It was important, then, to measure the output power spectra from the laser diode. A SPEX 3/4 meter Czerny-Turner spectrometer was used. Some representative spectra for various drive currents are shown in Fig. 2. Clearly noticeable is the broadening of the spectra (with resulting decrease in overall power) as the drive current is lowered.

At high currents (Fig. 2a), the laser spectrum is a narrow peak (with perhaps two modes) leading to a relatively long coherence length:

$$1_c = \frac{\lambda^2}{\Delta\lambda} = 2.3mm$$

making initial alignment relatively easy. Then, as current is reduced, less stimulated gain in the laser results in more longitudinal modes present and a relatively larger percentage of the smooth spontaneous emission floor (Figs. 2b and 2c).[1] As current is reduced further below threshold, the output becomes predominantly broadband spontaneous emission (>10nm) when the laser is operating essentially as an LED (Fig. 2d). For the 16.6nm spectral width of Fig. 2d, the coherence length is:

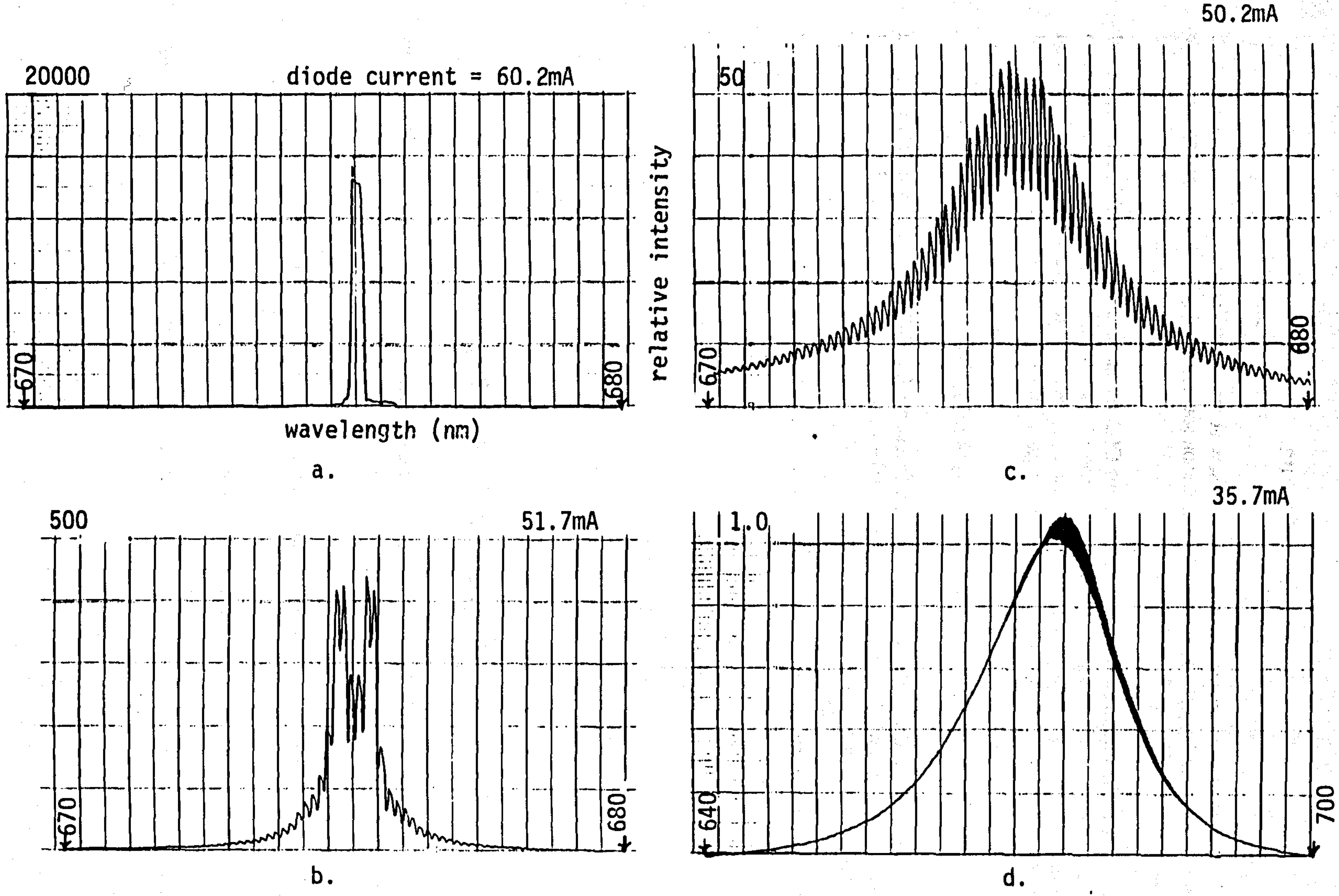

Fig. 2. Laser diode spectra for four different drive currents, showing broadening. Note the expanded wavelength scale in "d."

$$l_c = \frac{\lambda^2}{\Delta\lambda} = 27.4\mu m.$$

At this point, if the interferometer alignment has been tuned to stay at maximum fringe contrast as the current is reduced, the laser source can then be replaced with the filtered xenon source, and the interferometer should still be balanced to a sufficiently small OPD to obtain fringes.

It is informative to calculate the interference fringe pattern versus OPD for the spectrum shown in Fig. 2c, typical of an intermediate drive current near threshold. The spectrum can be approximately modeled as the sum of two parts, a lorentzian-shaped curve representing the spontaneous emission background and a smaller periodic portion (conveniently modeled as the product of a cosine function with a gaussian envelope) representing the longitudinal modes of stimulated emission:

$$S(v) = aL(v) + bG(v) \cdot \cos(2\pi v / \Delta v')$$

where $S(v)$ is the power spectral density, $L(v)$ is a lorentzian function with FWHM linewidth of Δv_L,$G(v)$ is a gaussian function with FWHM linewidth of Δv_G, and a and b are relative spectral strengths. Figure 3 shows the total power spectral density modeled as a sum of these functions.

The fringe visibility $V(x)$ in the interferogram resulting from this source can then be obtained from the following relationships[2]:

$$V(x) = K_1 \gamma(x/c)$$

$$\gamma(\tau) = \left| \frac{\int_0^\infty 4S(v) e^{-j2\pi v\tau} dv}{\int_0^\infty 4S(v) dv} \right|$$

$$= \left| \int_0^\infty S(v) e^{-j2\pi v\tau} dv \right| \equiv K_2 \left| \Im^+ S(v) \right|$$

where $V(x)$ is the fringe visibility, $\gamma(\tau)$ is the modulus of the complex degree of coherence, K_1 and K_2 are constants, and $\Im^+$ represents the Fourier transform for positive frequencies only.

The Fourier transformation can be performed on each component of $S(v)$, then the modulus combined as indicated in the lower part of Fig. 3. The transform of the lorentzian part leads to an exponential term in the fringe visibility with a FWHM width of:

$$\nabla\tau_L = 0.44/\Delta v_L$$

while the cosine with gaussian envelope results in two gaussians positioned on either side of the exponential by a displacement of:

$$\nabla\tau' = 1/\Delta v'$$

with each gaussian having a FWHM width of:

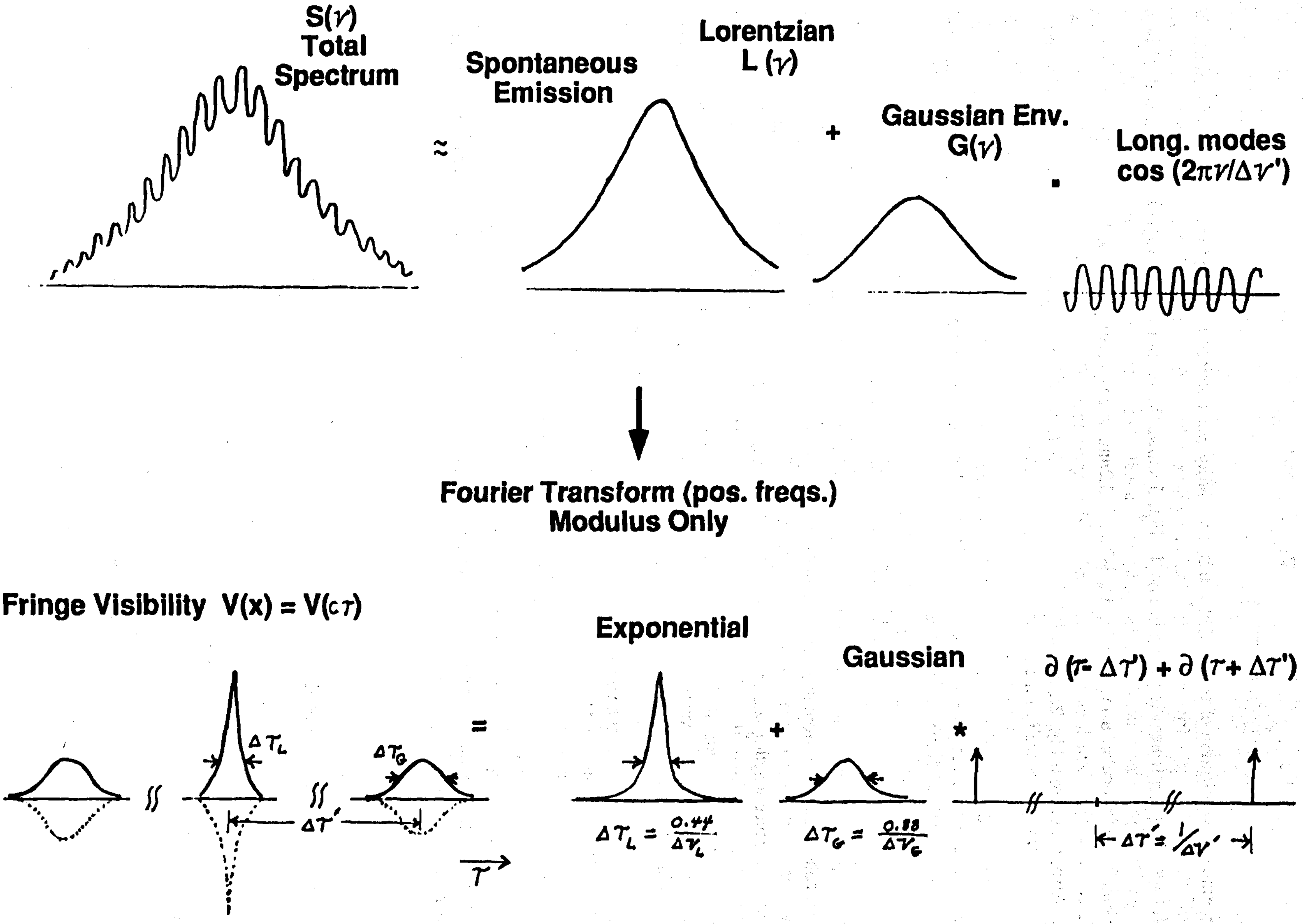

Fig. 3. Model of power spectrum of laser diode at intermediate drive current, with theoretical prediction of its resulting fringe visibility envelope.

$$\nabla\tau_G = 0.88/\Delta\nu_G.$$

An experimental verification of this predicted fringe visibility was obtained by using the laser diode as a source in the fiber interferometer at a drive current (49.6mA) near the conditions for which Fig. 2c applies. The experimental setup for recording the fringes is shown in Fig. 4. Fig. 5 shows the resulting interferogram. Note that the fringe visibility follows the same general form as predicted by the above transformation results and as shown in the lower left of Fig. 3. In particular, using Fig. 2c, $\Delta\lambda_L \approx \Delta\lambda_G \approx 3.2$nm, so $\Delta\nu_L \approx \Delta\nu_G \approx 2.11 \times 10^{12}$Hz. Thus $\Delta x_G = c\Delta\tau_G = 0.88c/\Delta\nu_G = 125\mu$m, which closely corresponds to the experimental FWHM in Fig. 5. Similarly, $\Delta x_L = c\Delta\tau_L = 63\mu$m. Also, again from Fig. 2c, $\Delta\lambda' \approx 0.133$nm, so $\Delta\nu' \approx 8.76 \times 10^{10}$ Hz. Thus $\Delta x' = c\Delta\tau' = c\Delta\nu' = 3.42$mm, which again corresponds well to the experimental value in Fig. 5.

Note incidentally that the coherence length of the central fringe envelope shown in Fig. 5 when the laser is driven at an intermediate drive current is about 60μm, which falls between the extremes at high drive current (2.3mm) and at low drive current (27.4μm), as expected.

4. SUMMARY AND CONCLUSIONS

The visible light laser diode proved useful as a variable coherence length source for fiber interferometry. The minimum coherence length from this visible light source was measured to be a few tens of micrometers. This occurs for drive current values below laser threshold, where the diode output is dominated by spontaneous emission. The maximum coherence length (≈2.5mm) occurs with high drive current (≈60mA), which shrinks the diode's spectral content to a few longitudinal modes. Note that the power output of the diode varies by about four orders of magnitude as the drive current is changed by a factor of two. For some applications, the low power levels corresponding to the wide spectral output may pose signal-to-noise problems. A desirable feature of a diode laser source would be tunability over a larger dynamic range of coherence lengths, and in particular, coherence lengths approaching a meter. The diode could then replace much larger, inefficient gas lasers in many interferometric applications. Even with the coherence length limitation of a few millimeters, the visible light diode proved to be a useful tool for balancing the arm lengths in a long fiber (Mach-Zehnder) interferometer.

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REFERENCES

1. Siegman, A.E., Lasers, University Science Books, Mill Valley, CA, 1986.
2. Goodman, J.W., Statistical Optics, John Wiley & Sons, New York, 1985.

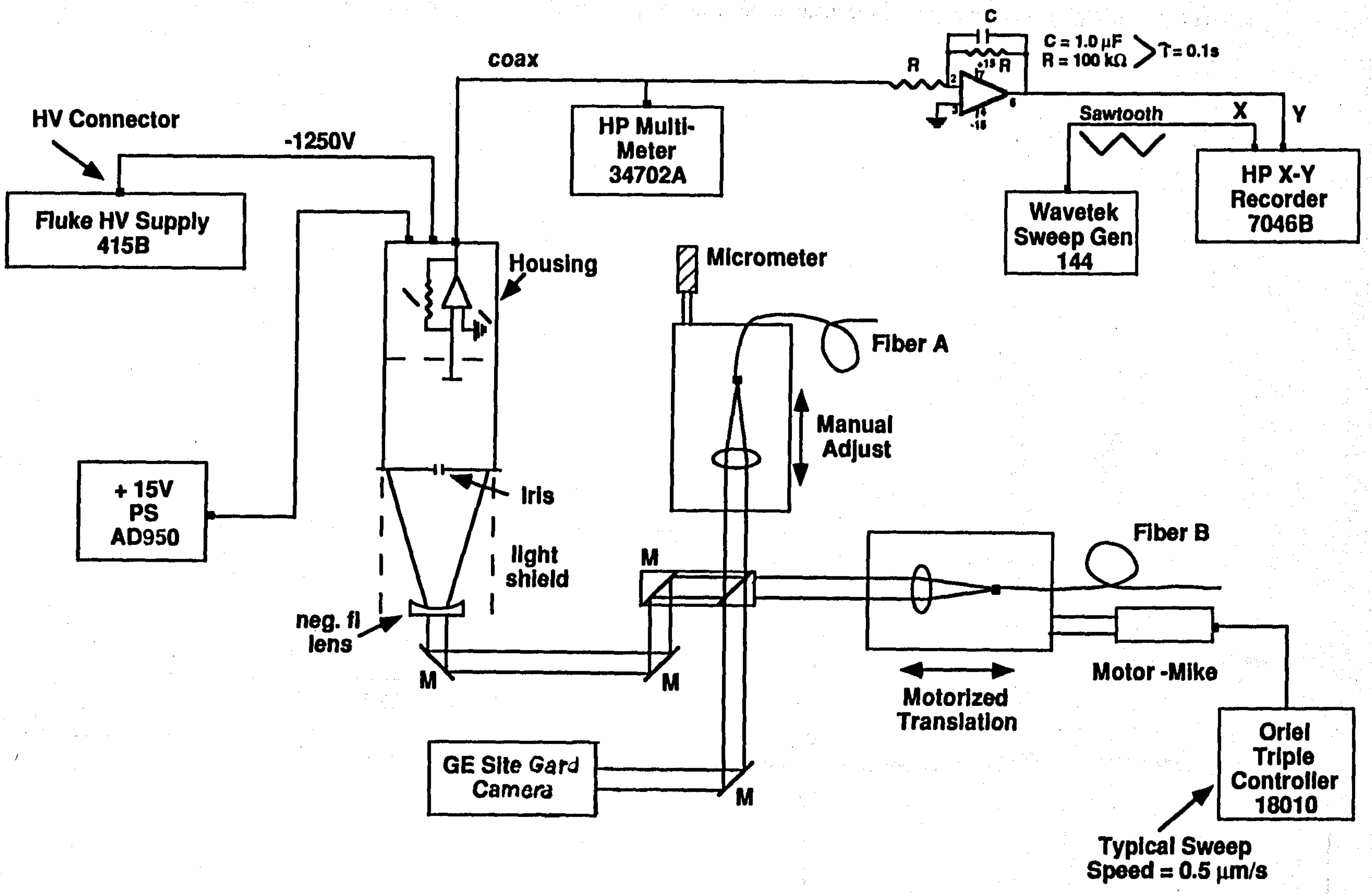

Fig. 4. Experimental setup for recording the fringes as OPD is varied.

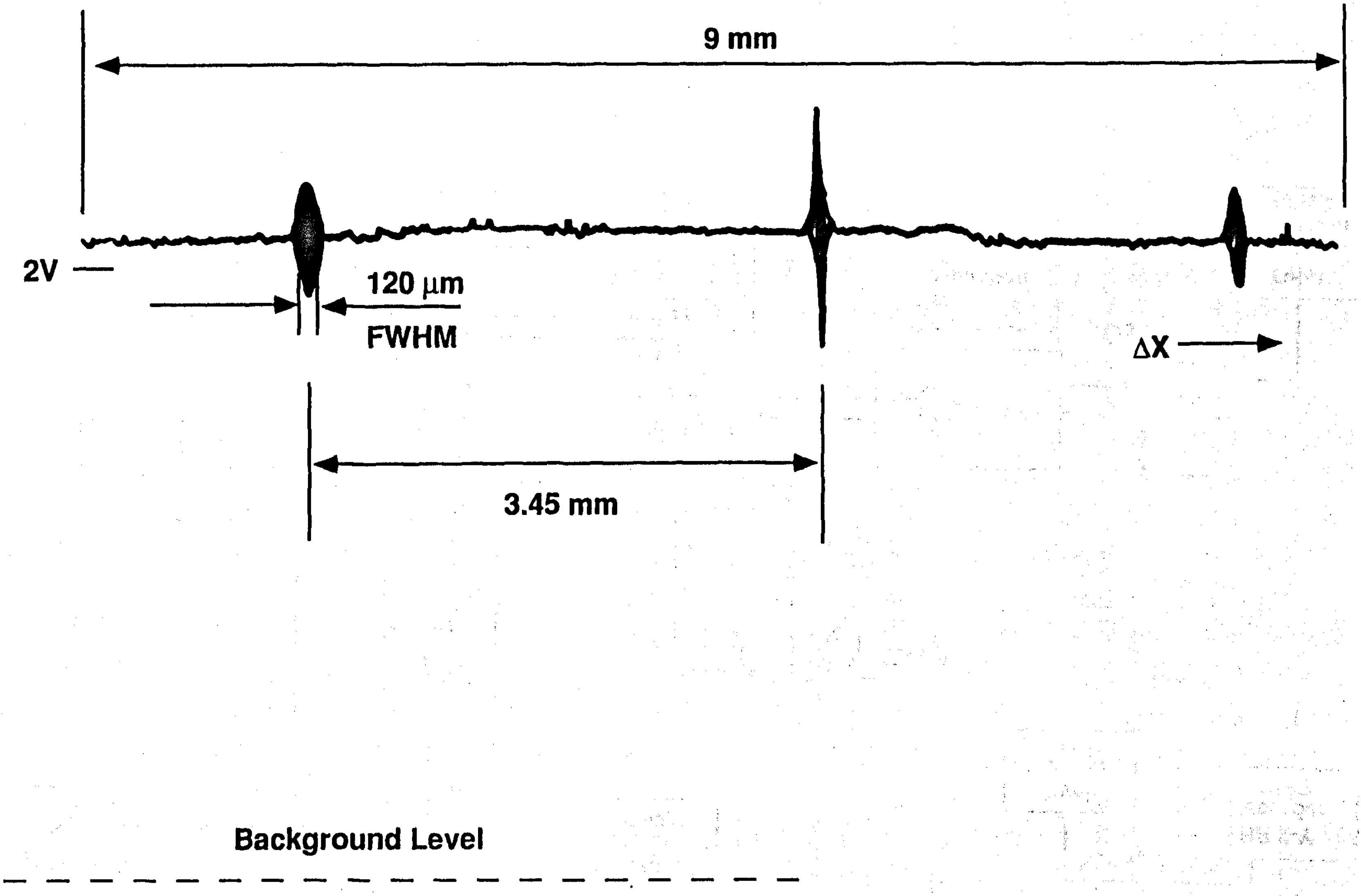

Fig. 5. Interferogram after traversing 60m fibers, using 670nm laser diode at an intermediated drive current of 49.6mA. The laser's power spectrum is approximately that shown in Fig. 2c. Compare the fringe visibility to the predicted pattern in the lower left of Fig. 3.