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Design of a Fiber-Optic Transmitter for Microwave Analog Transmission With High Phase Stability

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The principal considerations in the design of fiber-optic transmitters for highly phase-stable radio frequency and microwave analog transmission are discussed. Criteria for a fiber-optic transmitter design with improved amplitude and phase-noise performance are developed through consideration of factors affecting the phase noise, including low-frequency laser-bias supply noise, the magnitude and proximity of external reflections into the laser, and temperature excursions of the laser-transmitter package.

I. Introduction and Overview

Phase-stable transmission of analog signals is crucial for ultrastable frequency-reference distribution, phased-array antenna synchronization systems, and radio science experiments. Better phase-noise performance from directly modulated semiconductor laser-diode fiber-optic systems is compulsory for precise distribution of next-generation frequency references with frequency stability of $10^{-15}/\tau$ [1], and for improved synchronization of large phased-array antenna systems.

It has been shown [2] that the phase noise of a radio-frequency (RF) signal transmitted over a fiber-optic link via direct modulation of a semiconductor laser diode is equal to the signal-to-noise ratio (SNR) of the link, determined by the intensity noise of the laser diode. While this is true at high offset frequencies ($f \geq 1$ MHz) from the RF carrier, the results of this study indicate that RF signals transmitted through a fiber-optic link by direct (current) modulation of a semiconductor laser diode acquire close-to-carrier phase noise (from 0.1 Hz to 10 kHz offsets) which can be much larger than the SNR of the link. Thus, it is noted that the recent dramatic improvements in the high-frequency noise characteristics of semiconductor laser diodes have not produced commensurate improvements in close-to-carrier RF phase-noise performance. Also, it appears that close-to-carrier RF phase noise is not determined by the relative intensity noise (RIN) of the laser in the modulation band, since lasers with widely varying levels of RIN have been found to yield similar close-to-carrier phase-noise performance.

In this article, characterizations of the close-to-carrier RF phase noise of fiber-optic links employing both Fabry-Perot (FP) and distributed-feedback- (DFB-) type laser diode transmitters are presented, as well as a discussion of the effects of bias current fluctuations, optical reflections, and temperature variations on the magnitude of the RF phase noise. From these findings, a set of specific criteria have emerged for the design of fiber-optic links with improved RF phase-noise performance.

II. Characterizations of Additive RF Phase Noise

The additive RF phase noise of two different fiber-optic links was measured using the phase-detector technique [3] driven by a 100-MHz signal from a hydrogen-maser frequency standard. The measurement system is illustrated in Fig. 1. The results of phase-noise measurements of fiber-optic systems employing both a multi-longitudinal-mode FP laser diode [4] and a single-longitudinal-mode DFB laser diode [5] are presented in Fig. 2. Both systems were operated with a 4-km length of fiber and low-reflection expanded-beam optical connectors. The DFB package incorporated a 30-dB internal optical isolator. The most surprising result is that the phase noise of the isolated DFB transmitter at 1 Hz is identical to that of the non-isolated FP transmitter, even though the SNR of the DFB laser is 15 to 20 dB better than the FP laser at 100 MHz.

Initially, it was suspected that the close-to-carrier phase-noise floor would be set by the magnitude of the low-frequency fluctuations of the laser-diode bias current. To quantitate this effect, the sensitivity of the RF phase noise to laser bias-current fluctuations was calculated by adding a small 5-Hz current modulation to the 31-mA direct-current bias [6]. This current modulation induced a phase-noise sideband at 5 Hz from the 100 MHz carrier, from which a bias current-to-phase noise conversion constant was derived.

The bias-current source noise was then measured from 1 Hz to 100 kHz, and the expected level of phase noise due to the bias-current fluctuations was calculated. This value is compared to the actual measured phase noise of the DFB laser-diode fiber-optic link in Fig. 3. The measured phase noise of the fiber-optic link is 35 dB above the theoretical minimum level set by the bias-current source noise. Therefore, it was concluded that bias-current source fluctuations are not responsible for the residual phase noise of the DFB laser link.

An investigation of the sensitivity of the phase noise and SNR to both optical reflections and temperature excursions was performed for the DFB laser link. Figure 4 illustrates the apparatus used for measuring the phase noise and SNR versus back-reflected power and laser-chip temperature. The laser was operated at a constant current of 31 mA for an optical power output level of 1.7 mW, 2.3 dBmo (dBmo = dB with respect to 1 mW of optical power). The temperature of the thermoelectric cooler inside the isolated laser package was maintained to within 0.01°C, adjustable in 0.1° steps [7].

Figure 5 illustrates the results of measurements of the RF phase noise at 100 MHz as a function of back-reflected power for the DFB link. The noise appears to depend linearly on the amount of back-reflected optical power. The top curve in Fig. 5 represents the effect of a reflection of −18.5 dBmo (return loss = 20.8 dB). These results suggest a simple relation which describes the amount of isolation required to render the laser insensitive to a reflection of a given power level, P_R,

$$\begin{aligned} I(P_R) &= S_\phi(1\ \text{Hz}, P_R) - S_\phi(1\ \text{Hz}, 0) \\ &= -65 - (-115) \\ &= 50\ \text{dB} \end{aligned} \tag{1}$$

where $I(P_R)$ is the additional isolation (in excess of the 30-dB internal isolator) in dB, $S_\phi(1\ \text{Hz},\ P_R)$ is the phase noise measured at the maximum reflected power level of $P_R = -18.5$ dBmo from Fig. 5, and S_ϕ (1 Hz, 0) is the phase noise measured with no reflected power (return loss $= \infty$) from Fig. 3. Therefore, to achieve the optimum phase-noise performance at 1 Hz with a reflection of P_R, it appears that 50 dB of additional isolation is required in addition to the 30-dB internal isolator, for a total of 80 dB.

The effect of back-reflected power on the high-frequency-intensity noise of the laser was investigated by looking at the wideband noise on a spectrum analyzer display while changing the amount of back-reflected optical power. However, the laser-intensity noise did not change linearly over the entire range of back-reflected power. For the same 30-dB increase in reflected power from $P_R = -45$ dBmo to −15 dBmo, only a 10-dB increase in the SNR was observed. The low-frequency roll-off of the optical receiver did not permit study of the intensity-noise at frequencies below 10 MHz, but the laser-intensity noise appeared to increase as $1/f$.

Using the results of the RIN measurements to determine the isolation required to render the laser insensitive to optical reflections, the following is obtained:

$$\begin{aligned} I(P_R) &= N_{RIN}(100\ \text{MHz}, P_R) - N_{RIN}(100\ \text{MHz}, 0) \\ &= 10\ \text{dB} \end{aligned} \tag{2}$$

where $N_{RIN}(100\text{ MHz}, P_R)$ is the RF noise-power level measured with the maximum optical reflection, and N_{RIN} (100 MHz) is the RF noise-power level with minimum optical reflection.

The value $I(P_R)$ obtained from the SNR measurement at 100 MHz is very different from the value obtained from the phase-noise measurement at 1 Hz from the carrier. Since the laser-intensity noise increases as $1/f$ at lower frequencies, a simple measurement of the intensity noise versus reflected power at the RF modulation frequency leads to a grossly incorrect estimate of the amount of isolation required for good close-to-carrier phase-noise performance.

The phase-noise level and SNR were found to be extremely sensitive to variations of the laser chip temperature, as illustrated in Figs. 6 and 7. Both the phase noise and RIN showed a periodic dependence on the chip temperature with a 3- to 5-dB amplitude over a period of 1°C. Figure 8 vividly illustrates the periodic variation of the relative group delay for the 4-km link as the laser-diode temperature was swept slowly from 25° to 50°C. The trend of the data follows the expected parabolic group delay-versus-wavelength characteristic for single-mode fiber with linear dispersion, but the rapid periodic fluctuation in the group delay is unexpected and, at present, unexplained.

III. Relationship of Laser-Intensity Noise to RF Phase Noise

In [2], it is shown that the intensity fluctuations of the laser will appear as close-to-carrier phase noise on an RF modulation signal. However, the more fundamental problem concerns the cause of the increased laser-intensity noise at low frequencies. Present theoretical models for semiconductor laser noise [8,9] predict laser-intensity noise to be white at low frequencies. However, a $1/f$ dependence of the low-frequency intensity noise has been observed in the optical output of DFB lasers [10,11], in agreement with the observations.

If the low-frequency laser-intensity noise were white, as predicted by theory, the close-to-carrier phase noise of fiber-optic links would also be white, and would have the same value as the SNR at larger offset frequencies. At present, however, it appears that the unexplained $1/f$ character of the laser-intensity noise limits the close-to-carrier phase-noise performance of analog fiber-optic links. Therefore, further research efforts to understand and reduce this noise are imperative for improved close-to-carrier phase-noise performance of fiber-optic links.

Other research [10] corroborates the measurements of this study, which indicate that optical reflections cause an increase in the magnitude of the $1/f$ component of the laser-intensity noise. Therefore, it would seem that any reflections in the coupling optics, insufficient antireflection (AR) coating on the collimating lens, or reflections from the optical-isolator components will cause increased low-frequency laser-intensity noise. Thus, the residual level of close-to-carrier RF phase noise from Fig. 2 measured with minimum reflected power may be caused by reflections from the optical surfaces between the laser and the optical isolator. This may explain why lasers with different magnitudes of RIN can display equal phase-noise magnitudes when no excess reflections are induced. More study of the effect of residual reflections from coupling optics is required to quantify their contribution to low-frequency intensity noise.

Finally, it was observed that the conversion of low-frequency intensity noise to close-to-carrier RF phase noise may possibly be used to advantage to stabilize the output of laser diodes. Since laser intensity is coupled to laser frequency and phase through the carrier-density of the gain medium, the phase noise induced on an RF modulation signal represents a "probe" of the laser carrier density fluctuations. Consequently, it may be possible to use a continuous RF phase-noise measurement to generate an error signal to feed back on the laser bias current, thereby stabilizing the laser intensity, frequency, and phase fluctuations. These ideas are the subjects of ongoing research by the authors.

IV. Design Considerations for Phase-Stable Semiconductor Laser Transmitters

To obtain optimum phase-noise performance from fiber-optic links subjected to unpredictable amounts of optical reflection, a fiber-optic transmitter package should incorporate the elements outlined in the preceding sections: high optical isolation, low-reflection coupling optics, and excellent temperature control. Conceptually, a transmitter employing these elements is illustrated in Fig. 9. It employs a wide-bandwidth, low-noise laser chip, a molded-glass aspheric collimating lens (AR-coated and located close to the laser-diode output facet), and two optical isolators in series to provide at least 60 dB of isolation. Even this amount of isolation may not be adequate for some applications where extremely high levels of reflected power are present. In these cases, additional external isolation could be added, provided the return loss of the external isolator is adequate and the intervening fiber is not subjected to flexure.

The key features of this design are that the laser beam is collimated and expanded using a single lens, and that the only back-reflection into the laser occurs within a few millimeters of the laser facet. It has been found [12] that optical reflections which occur within 5 mm of the laser-diode facet degrade noise performance very little. Then, the reflection from the first surface of the 60-dB isolator can be practically eliminated by an AR coating and a slight off-axis tilt. Following the isolator, a second molded lens would then focus the beam into a single-mode fiber.

The key component for the realization of this design is the molded glass aspheric lens, which provides the highly collimated beam necessary for maximum isolator performance. These types of lenses are currently used to focus the laser outputs in compact disc players, and represent a mature technology; however, the beam parameters of the laser must be tightly controlled in processing to insure efficient power transfer through the lens. An added benefit of using multiple isolators is reduced sensitivity of the isolation to fluctuations in ambient temperature.

V. Summary and Conclusions

In the study described here, the close-to-carrier phase noise added to RF modulation signals by fiber-optic links based on direct current modulation of a semiconductor laser diode was characterized. This additive RF phase noise is due to the low-frequency laser-diode intensity noise, and can be significantly larger than the signal-to-noise ratio of the link at the RF modulation frequency. Thus, the recent improvements in semiconductor laser-noise performance have not necessarily resulted in fiber-optic links with improved RF phase-noise performance.

It has been determined that the magnitude of the RF phase noise due to the laser-intensity noise is sensitive to the amount of optical power reflected into the laser cavity. Also, the phase-noise magnitude, SNR, and relative group delay of fiber-optic transmitters have been found to be extremely sensitive to laser-chip temperature. At present, it appears that the intensity noise generated in the semiconductor laser diode is the principal limitation of close-to-carrier phase stability in analog fiber-optic systems, but this point requires further study.

The results of the study suggest several key features which appear to be prerequisites for achieving improved RF phase stability in a fiber-optic transmitter. The key features are

(1) greater than 60-dB optical isolation of the laser diode from all reflections

(2) less than 5 mm of distance from the laser-diode facet to the first optical reflection

(3) excellent temperature control of the laser chip, to better than 0.1°C

Such a design should permit phase-stable RF transmission over fiber-optic links subjected to time-varying reflections due to vibration and flexure of the fiber-optic cable. Work is in progress by the authors to characterize the performance of fiber-optic systems which incorporate these features to various degrees.

Acknowledgment

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References

[1] R. T. Wang, G. J. Dick, and D. M. Strayer, "Operational Parameters for the Superconducting Cavity Maser," *Proc. 12th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, Tyson's Corner, Virginia, pp. 345–354, November 29–December 1, 1989.

[2] K. Y. Lau, "Microwave phase stability of directly modulated semiconductor injection lasers," *Appl. Phys. Lett.*, vol. 52, no. 17, pp. 1377–1378, April 25, 1988.

[3] Hewlett-Packard, "Understanding and Measuring Phase Noise in the Frequency Domain," Application Note 207, Palo Alto, California, October 1976.

[4] Ortel Corporation, "3510B RF/Microwave Fiber-Optic Transmitter," manufacturer's data sheet, Alhambra, California, February 1988.

[5] Mitsubishi Electric Corporation, "FU-45SDF-3 DFB-Laser Diode Module," manufacturer's data sheet, Tokyo, Japan, 1989.

[6] ILX Lightwave Corporation, "Model LDX-3620 Ultra-Low Noise Current Source," manufacturer's data sheet, Bozeman, Montana, 1989.

[7] ILX Lightwave Corporation, "Model LDT-5910 Thermoelectric Temperature Controller," manufacturer's data sheet, Bozeman, Montana, 1989.

[8] K. Vahala and A. Yariv, "Semiclassical Theory of Noise in Semiconductor Lasers: Parts I and II," *IEEE J. Quantum Electron.*, vol. QE-19, no. 6, pp. 1096–1109, June 1983.

[9] P. Spano, S. Piazzolla, and M. Tamburini, "Phase Noise in Semiconductor Lasers: A Theoretical Approach," *IEEE J. Quantum Electron.*, vol. QE-19, no. 7, pp. 1195–1199, July 1983.

[10] Y. C. Chen, "Phase noise characteristics of single mode semiconductor lasers with optical feedback," *Appl. Phys. Lett.*, vol. 44, no. 1, pp. 10–12, January 1, 1984.

[11] K. Kikuchi, "Effect of $1/f$-Type FM Noise on Semiconductor Laser Linewidth Residual in High-Power Limit," *IEEE J. Quantum Electron.*, vol. 25, no. 4, pp. 684–688, April 1989.

[12] K. Sato, "Intensity Noise of Semiconductor Laser Diodes in Fiber-Optic Analog Video Transmission," *IEEE J. Quantum Electron.*, vol. QE-19, no. 9, pp. 1380–1391, September 1983.

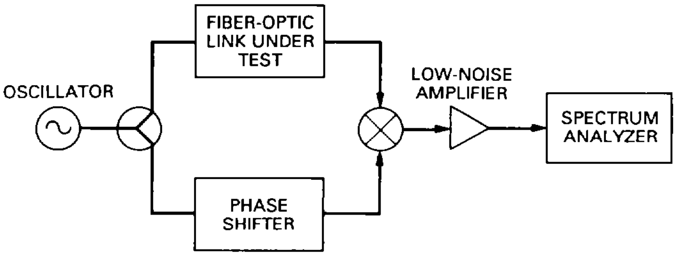

Fig. 1. RF phase-noise measurement system.

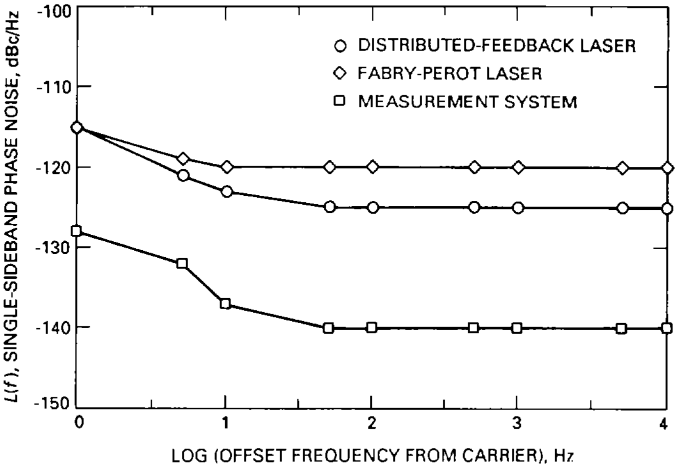

Fig. 2. RF phase noise at 100 MHz for Fabry-Perot and DFB laser-diode transmitters; measurement-system noise.

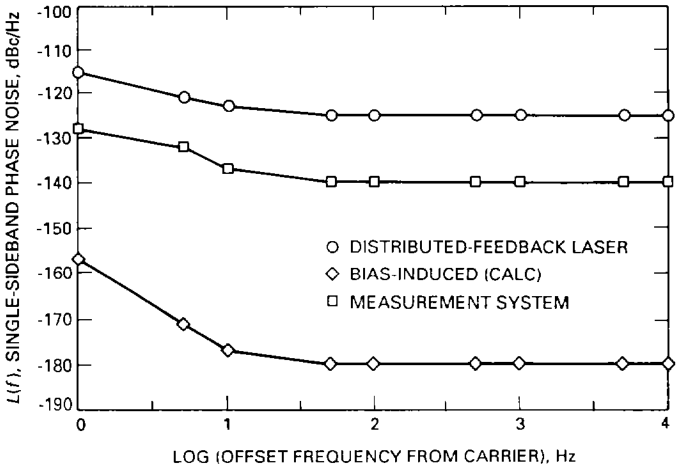

Fig. 3. RF phase noise for DFB laser transmitter, measurement noise floor, and calculated current-source-induced phase noise.

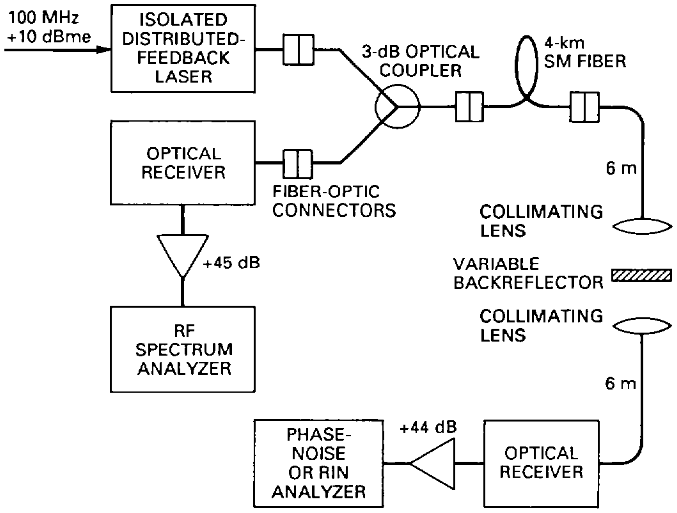

Fig. 4. Measurement system for investigation of RF phase noise and laser intensity versus back-reflected optical power.

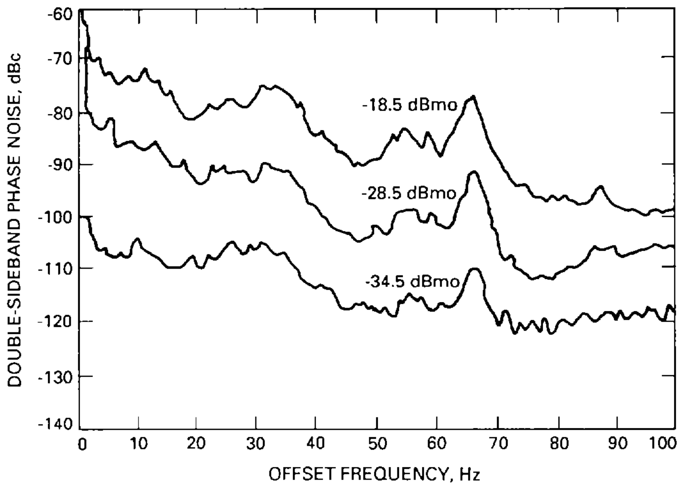

Fig. 5. RF phase noise versus reflected optical power for DFB transmitter with 30-dB internal isolator.

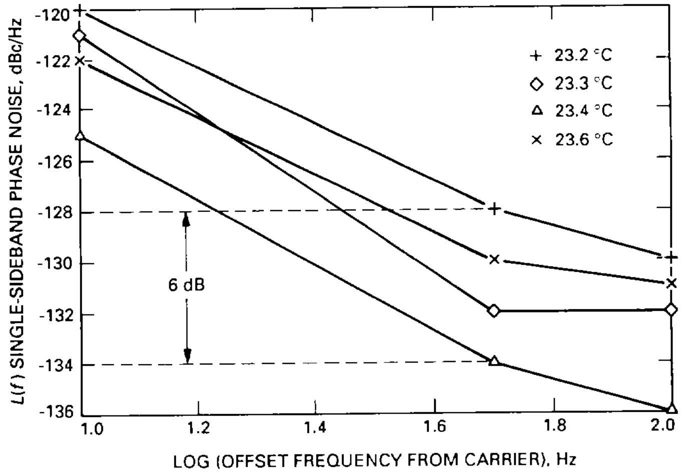

Fig. 6. RF phase noise of DFB laser transmitter versus laser-chip temperature.

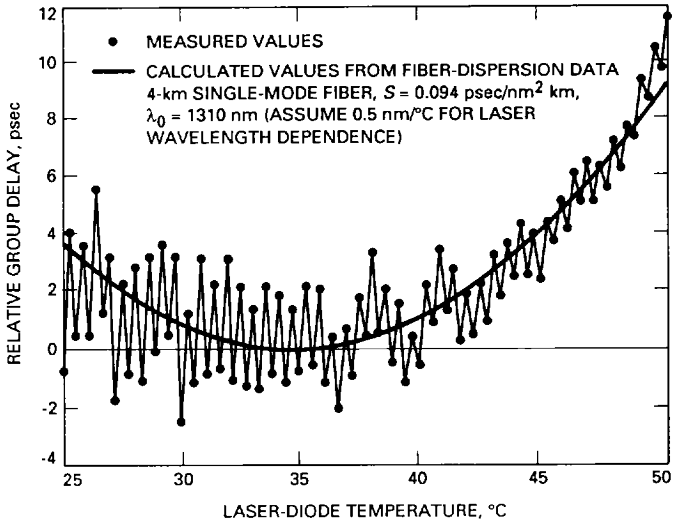

Fig. 8. Relative group delay of DFB laser transmitter versus laser-chip temperature.

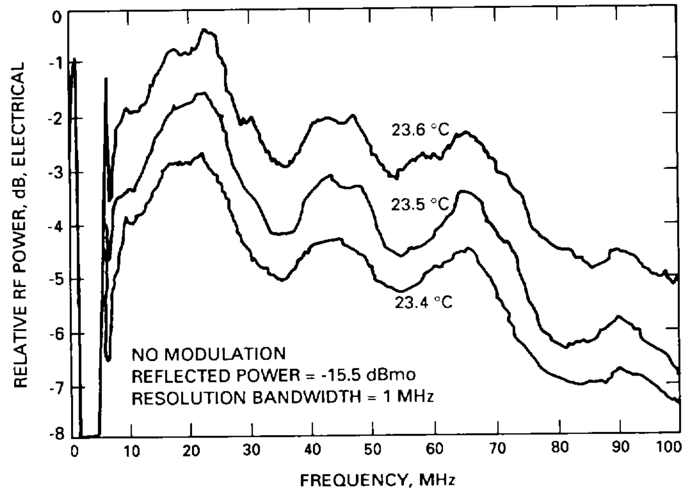

Fig. 7. Intensity noise of DFB laser transmitter versus laser-chip temperature.

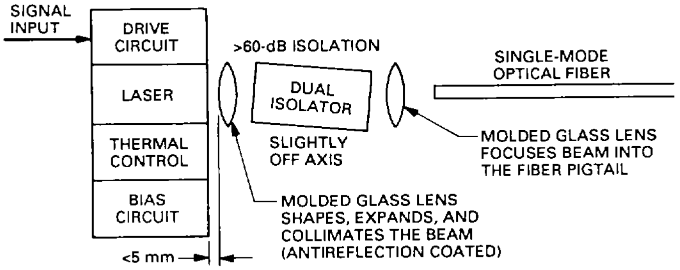

Fig. 9. Proposed laser transmitter design concept for improved phase stability.