Performance of Low-Cost Commercial Fiber–Optic Transceivers for Reference Frequency Distribution

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Abstract

Precision time and frequency reference signals have been effectively disseminated using high–quality intricate fiber–optic distribution systems. The quality of signals distributed by such systems is excellent, but the cost of these systems makes them unavailable to many potential users. In this paper, a study of signal quality maintained using inexpensive commercial transmitter/receiver pairs is undertaken. Seven different transmitter/receiver pairs obtained from four different manufacturers have been thoroughly tested using a 5 MHz sinusoid derived from a precision, temperature–controlled, crystal–controlled oscillator. The electrical signal output from each fiber–optic receiver was tested for spectral purity, single–sideband phase noise, and AM noise, and the results are tabulated and discussed without identification of the manufacturer or the equipment model number.

INTRODUCTION

One advantage of maintaining atomic frequency standards is that their reference frequency signals can be distributed to a number of users who need an precision common time base, accurate time, or a local oscillator with minimal long–term drift. At the Applied Physics Laboratory (APL), for example, atomic frequency references are distributed to the calibration laboratory for the calibration of long–term drift in quartz oscillators that are in precision measurement equipment, and also to satellite communications and tracking facilities for use as a local oscillator. One of the difficulties associated with a remotely located atomic frequency standard is that its signals tend to be degraded by transmission over long distances. The time and frequency laboratory at APL, for example, distributes 1, 5, and 10 MHz frequency references to eight facilities over distances up to 3000 feet.

Unfortunately, long interbuilding connections typically share cable trays and underground conduits with digital computer–network cables and 60 Hz power cables. Frequency–reference signals are often badly distorted by induced electrical interference as they are distributed via coaxial cables. At APL, for example, the 60 Hz sine wave superimposed on some distributed 5 MHz signals was large enough to trigger, and be displayed by, an oscilloscope.

A typical application at APL usually requires the distribution of both 5 MHz and 1 pps signals in the same cable bundle. When these signals travel side by side for 3000 ft in parallel coaxial cables, the potential for cross talk exists.

To minimize electrical interference and distortion, construction of a multichannel fiber–optic transmission network was initiated at APL. Currently over 75 channels of information (including 1, 5, and 10 MHz frequency references, and IRIG B and 1 pps reference signals) are distributed by APL's time and frequency laboratory; 30 of these lines are interbuilding connections. Monetarily, it is impractical to implement 30 interbuilding connections with customized analog fiber–optic links, which would cost thousands of dollars per channel. We therefore began testing inexpensive commercial fiber–optic transmitters and receivers that were designed for video signal transmission as a means of disseminating our reference signals.

In this study, seven different fiber–optic transmitter/receiver pairs from four different manufacturers were tested to verify the extent to which they degrade the single-sideband phase noise, harmonic distortion, spurious noise, and AM noise of a 5 MHz sinusoid derived from a precision, temperature–controlled, crystal–controlled oscillator. The test results are summarized here without identification of the manufacturer or the model number. The systems we tested ranged in price from $600 to $10,000 per transmitter/receiver pair, with most of the systems priced at the low end of that range. The prices per transmitter–receiver pair of the systems were as follows:

System A	$600	System B	$700
System C	$700	System D	$2850
System E	$3800	System F	$10,000
System G	$700		

By comparison, the cost of APL's commercial 50Ω buffer–amplifier system with coaxial–cable distribution (when fully populated, resulting in minimum cost on a per–channel basis) is approximately $350 per channel.

APL currently maintains 14 fiber–optic distribution lines, consisting exclusively of equipment costing less than $1000 per transmitter/receiver pair. In each case, the fiber–optic systems have improved the reliability of signal transmission through the elimination of either electrical surges caused by induced voltages (such as lightning) or mismatched terminations (or a direct short) by the user at his end of the distribution cable. Fiber–optic distribution has also drastically improved the quality of the distributed signals by greatly reducing electrical interference.

EXPERIMENTAL PROCEDURE

The seven systems tested here are designated System A through System G. The output of each system was tested for single–sideband phase noise performance, harmonic and spurious noise, and AM noise. All tests were performed using the transmitter/receiver pair to transmit a low–phase–noise 5 MHz sinusoid derived from a precision, temperature–controlled, crystal–controlled oscillator. The same reference oscillator was used to test each system and to determine the noise floor of each. The oscillator was used instead of an atomic frequency standard because it exhibits better phase–noise performance and lower–level harmonics in its output than does a typical atomic frequency standard. The oscillator's performance is illustrated in Figures 1, 2, and 3.

For the tests, each transmitter and receiver pair was connected by a short fiber-optic cable (less than 50 feet long). When possible, the tests were repeated using a 3200 ft, 250/62.5μm diameter multimode fiber. When availability allowed, more than one transmitter/receiver pair representative of each system was tested.

Phase noise tests were conducted using an HP3048A phase noise test system, which was calibrated (traceable to NIST) to be accurate to within ±2 dB over the frequency range of interest. The fiber–optic systems were tested over the frequency range of 0.1 Hz to 100 kHz from the carrier frequency. The results of each test are presented individually in graphical form and are discussed collectively. It is clear from Figure 1 and Figures 5a through 10a that the fiber–optic systems measurably degraded the phase noise of the reference oscillator at frequencies greater than 1 Hz from the carrier.

In some phase noise tests, buffer amplifiers were required to maintain specified signal levels. Whenever buffer amplifiers were used, the HP3048 phase noise system was recalibrated with the amplifiers included to ensure that the noise floor of the system with the buffers was well below that exhibited by the outputs of the fiber–optic systems. AM noise tests were also performed using the HP3048A phase noise system over the frequency range of 1 Hz to 100 kHz from the carrier frequency.

The spectral purity of the reference oscillator and the systems under test was verified with an HP8560A spectrum analyzer that was set for a frequency range of 1 to 51 MHz, with a video bandwidth and resolution bandwidth of 10 kHz. These settings provided a clear picture of the frequency spectrum of the'devices under test.

The single–sideband phase noise of the reference oscillator used throughout the testing is shown in Figure 1, a plot of its spectral purity appears in Figure 2, and its AM noise is presented in Figure 3. As will be seen, the reference oscillator exhibits much better phase noise performance beyond 1 Hz from the carrier and has a much cleaner frequency spectrum than any of the fiber–optic systems can maintain, so the numbers seen in the test results are truly attributable to the optical transmitters and receivers being tested.

DESCRIPTION OF THE SYSTEMS

SYSTEM A

System A consists of a stand–alone transmitter and receiver pair that cost $600. Three identical models were available and tested. The system uses an LED light source at 850 nm for light transmission, and light is transmitted through 205/62.5-μm diameter multimode fibers. The system has an input frequency range of DC to 60 MHz, and its electrical output can be adjusted from 50 mV to 2 V p-p.

SYSTEM B

System B consists of a rack–mounted system that costs approximately $700 per transmitter/receiver pair when the rack chassis is fully populated. The rack chassis holds approximately 10 plug–in cards, with up to two transmitters or receivers on each card. Its operational frequency range is from near DC to 20 MHz, with an electrical output amplitude that is adjustable up to 3 V p-p. This system uses an LED operating at 850 nm as its light source and 62.5 μm multimode fibers connected the transmitter and receiver. Two System B transmitter/receiver pairs were available for testing. The performance of this system was partially limited by the presence of noise added by a 1 pps signal being distributed by a transmitter on the same chassis, although the manufacturer claims that this system is capable of distributing both sinusoidal and pulsed signals from the same chassis.

SYSTEM C

System C consists of the same equipment as System B, but with the transmitter distributing the 1 pps signal removed. There is a noticeable improvement in the system's performance with the removal of the 1 pps signal lines. A comparison of the system with and without the 1 pps lines active is important because it is not uncommon for a timing station to distribute both 5 MHz frequency references and 1 pps timing references.

SYSTEM D

System D consists of a stand–alone transmitter/receiver pair that costs $2850, and operating with an 1300-nm LED as its light source. Only one transmitter/receiver pair of this type was available. The system's frequency range is 5 to 125 MHz, and its electrical output is approximately -10 dBm. Connector incompatibility prevented this system from being tested over the 3000 ft cable.

SYSTEM E

System E consists of a stand–alone transmitter/receiver pair that costs $3800. This system uses a 1350-nm laser transmitter and single-mode optical fiber for interconnection; therefore, it could not be tested with the 3000-ft multimode cable. Only one such system was available for test. Its operating frequency range is 5 to 300 MHz, with an output power near -25 dBm.

SYSTEM F

System F is also a stand–alone system using a 1350-nm laser light source, and single-mode optical fiber interconnection. The system costs $10,000 per channel, and only one transmitter/receiver pair was available. Its operating frequency range is 5 MHz to 3 GHz.

SYSTEM G

System G is a rack–mounted system that consists of a chassis with ten plug–in slots, and the ability to house two transmitters or receivers in each slot. When the chassis is fully populated, the system costs $700 per channel, and uses an 850-nm LED as a light source. Although similar, System G and System B were supplied by different manufacturers.

EXPERIMENTAL RESULTS

The results of the single–sideband phase noise tests and spectral analyses of each individual system appears in Figures 5 through 11, and is summarized in Table 1. Figure 5a shows the single–sideband phase noise of System A's output when transmitting the reference oscillator through a short optical fiber, and Figure 5b shows the spectral purity of its output when transmitting the same signal. Figures 6 through 11 show the similar two measurements for Systems B through G, respectively. Table 2 summarizes the AM noise measured in the outputs of the reference oscillator and in the fiber–optic links as a function of frequency.

Three pairs of System A equipment were available for testing. Each one was tested with both a 10 ft and a 3200 ft multimode fiber. Figure 5 is representative of the results of the six test runs performed on System A. The single–sideband phase noise curves obtained from all three receivers with the long and short fibers exhibited a noise floor of 115 ± 4 dBc/Hz for frequencies greater than 10 Hz from the carrier frequency. In all three cases, the phase noise floor was 2 to 3 dB lower when the 3200 ft fiber was used for signal transmission.

The frequency spectrum shown in Figure 5b is typical of that seen in all six tests of the transmitter/receiver pairs of the type used in System B. The first harmonic ranged from 36 to 50 dB below the carrier, and the second harmonic ranged from 35 to 45 dB below the carrier. The higher harmonics were insignificant, if present at all, and there were no cases with spurious signals other than those that were harmonically related.

The excessive spurious signals seen in the phase noise characteristic of System B (Figure 6a) were caused by the presence of a 1 pps transmitter in the rack chassis used to supply power to the plug–in transmitter–receiver pairs under test. Two pairs of equipment were available for testing, and both showed similar phase noise response; the phase noise of the two transmitter/receiver pairs were within 3 dBc/Hz of each other. The presence of the 1 pps transmitter in the system chassis caused an excessive number of spurious signals in the systems phase noise between 5 and 100 Hz; similar spurious signals were seen over the same frequency range in the AM noise measurements for System B. In both receiver's outputs, the first and second harmonics are between 37 and 44 dB below the carrier.

In order to find the ultimate performance of the equipment being tested, the tests were repeated with the 1 pps transmitter removed from the rack chassis that housed the transmitter/receiver pairs. After the 1 pps transmitter was removed, the System B equipment was redesignated as System C to differentiate the test results from the original System B tests. When the systems were tested with a short optical fiber interconnection, the first System C transmitter/receiver pair achieved a noise floor of -115 dBc/Hz. The second System C transmitter/receiver pair exhibited a noise floor of -125 dBc/Hz, 10 dBc/Hz below the noise floor the same transmitter/receiver pair achieved with the 1 pps transmitter in the chassis. Phase noise tests were repeated with the 3200 ft optical fiber, a length slightly longer than System C's specified range, which resulted in the phase-noise floor rising to -100 dBc/Hz.

The first harmonic was roughly 45 dB below the carrier level, and the second harmonic was near 50 dB below the carrier. As is evident by comparing Figures 7b and 8b, the noise floor in the frequency spectrum of System C was 10 dB below that of System B, showing the effect of the 1 pps signal's presence in System B.

Only one transmitter/receiver pair representative of System D, System E, and System F were available for testing. System D and System E were manufactured by the same manufacturer for analog transmission over a similar frequency band. The primary difference between the systems is the light source; System D uses an LED and System E uses a laser. Both systems achieved a noise floor of -120 dBc/Hz. The first and second harmonics in the output of System D were 40 and 50 dB below the carrier level, respectively, whereas in System E both the first harmonic and the second harmonic were 37 dB below the carrier level.

System F, which is considerably more expensive than all the other systems, exhibited a noise floor of

-125 dBc/Hz, with the first and second harmonics 38 and 50 dB below the carrier level, respectively.

System G has 75-Ω electrical inputs and outputs, but both the reference oscillator and the HP3048A are configured for 50-Ω systems, requiring impedance matching networks to interconnect the devices. In is possible that those impedance matching networks may have limited the test results of System G, although its measured performance compares favorably with the other systems. System G exhibited a single–sideband phase noise floor of -118 dBc/Hz, with the first harmonic 36 dB below the carrier level.

As can be seen in Table 2, each of the transmitter/receiver pairs significantly degraded the AM noise characteristics of the reference oscillator. With the exception of System B, each system achieved an AM noise floor in the neighborhood of -120 dBc/Hz. The reference oscillator's AM noise floor was closer to -150 dBc/Hz. No AM noise measurements were made on System A. During the time System A was available for testing, the AM noise measurement system was being calibrated and was not available for use.

CONCLUSIONS

The most interesting result of testing these many fiber–optic systems is that they all achieved a single–sideband phase noise floor of -115 to -125 dBc/Hz. This noise floor was amazingly consistent across the tests even though these systems used different light sources and frequencies, they varied widely in cost, and they were manufactured by many different manufacturers. Since a number of examples representative of Systems A and C were available, they were tested in the full permutation of configurations; that is, System A transmitter 1 was tested with System A receiver 1, 2, and 3, etc. From these tests, it is clear that, at least for these systems, the phase noise in the output signal is not completely limited by either the transmitter or the receiver, but rather by a combination of both elements.

It is also interesting to note that fiber–optic cable length can have a measurable effect on the signal quality. As was seen in System A, for example, the phase noise for frequencies greater than 10 Hz from the carrier frequency was approximately 3 dBc/Hz lower at the longer fiber lengths than it was for the shorter fibers.

It is clear that all the fiber–optic systems significantly degrade the single–sideband phase noise, AM noise, and harmonic distortion of a quality oscillator. The levels of performance achieved by these systems is acceptable for reference frequency distribution if the transmitted signals are being used as a common time base for test equipment, or as a reference for a system that phase locks its own internal voltage controlled oscillator to the transmitted reference.

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Table 1. Single–sideband phase noise performance of the fiber-optic systems.

	Single–sideband phase noise (dBc/Hz)							
Freq. (hz)	Reference	System A	System B	System C	System D	System E	System F	System G
0.1	- 90	- 85	- 90	- 90	- 90	- 90	- 90	- 80
1	-120	-115	-115	-115	-115	-110	-117	-113
10	-145	-115	-116	-125	-120	-118	-124	-118
100	-152	-115	-116	-125	-120	-118	-124	-119
1k	-153	-115	-116	-125	-119	-119	-124	-119
10k	-153	-115	-116	-125	-120	-119	-124	-119
100k	-153	-115	-116	-125	-118	-119	-124	-119

Table 2. AM noise response of the fiber-optic systems.

	AM noise response (dBc/Hz)						
Frequency (Hz)	Reference	System B	System C	System D	System E	System F	System G
1	-125	-112	-115	-108	-90	-120	-110
10	-133	-115	-121	-110	-100	-120	-115
100	-140	-112	-121	-115	-105	-120	-117
1000	-148	-113	-120	-118	-115	-120	-117
10k	-153	-112	-119	-118	-120	-120	-117
100k	-154	-111	-117	-118	-120	-120	-117

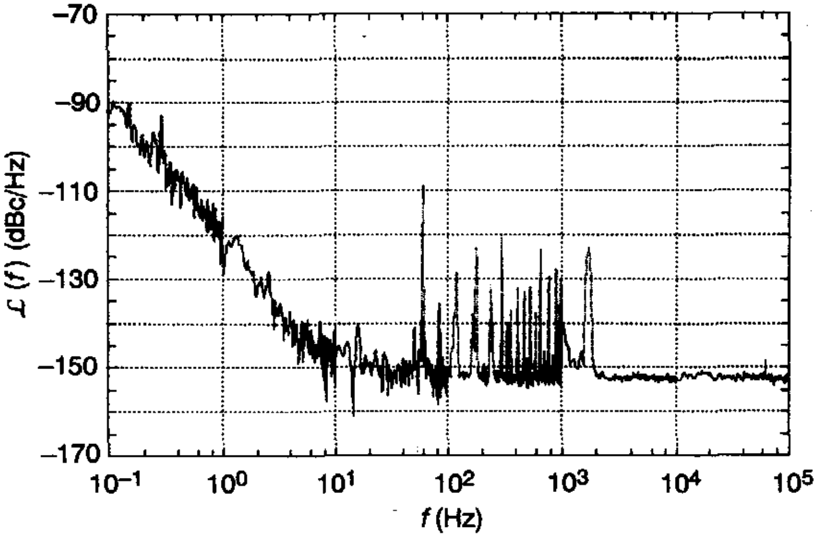


Figure 1. Reference oscillator single-sideband phase noise.

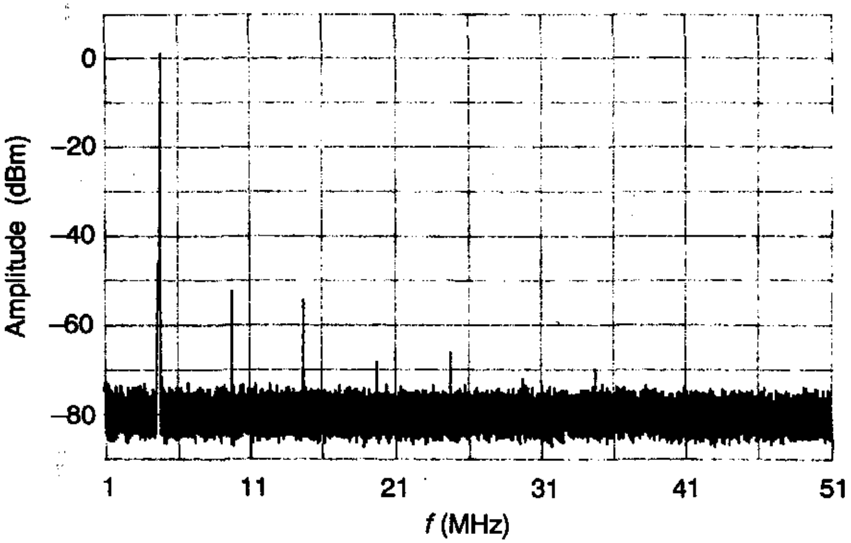


Figure 2. Reference oscillator frequency spectrum.

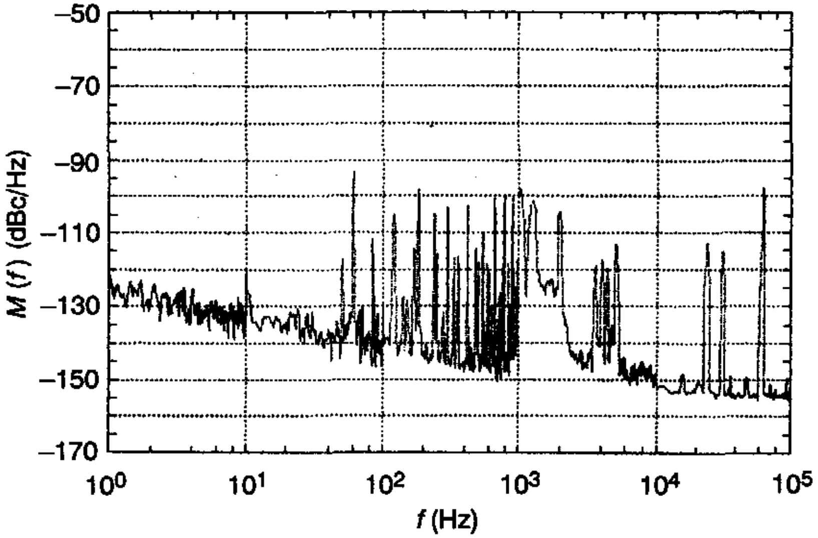


Figure 3. Reference oscillator AM noise.

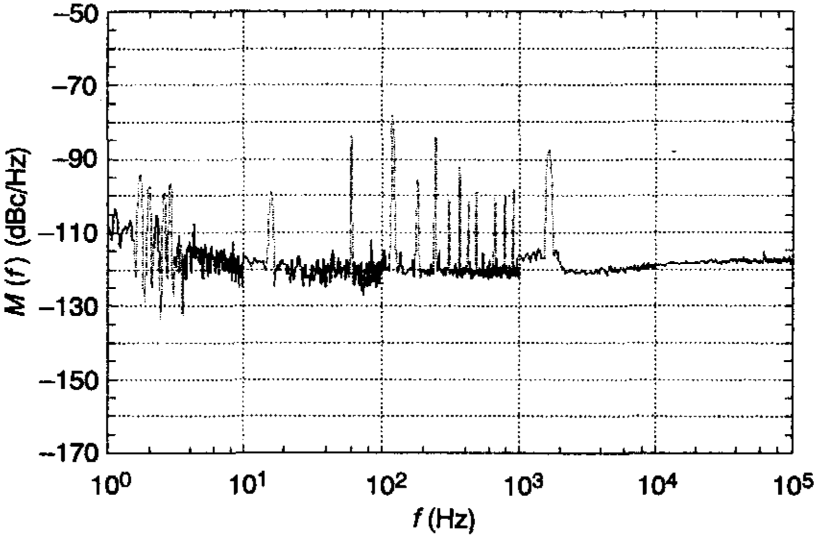
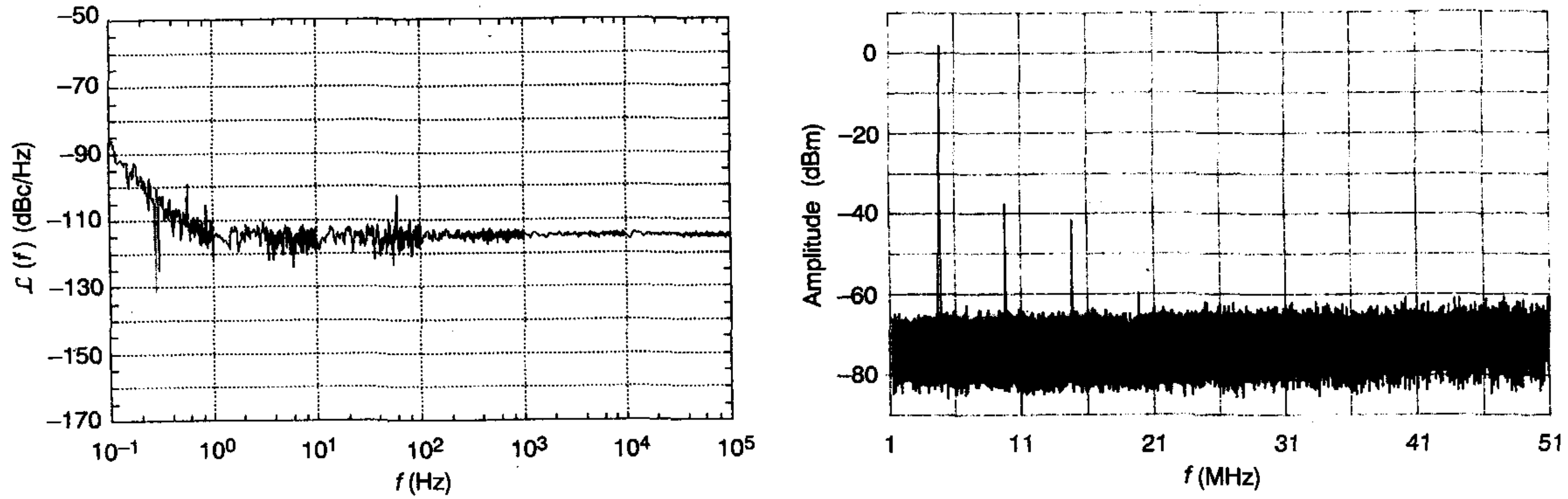


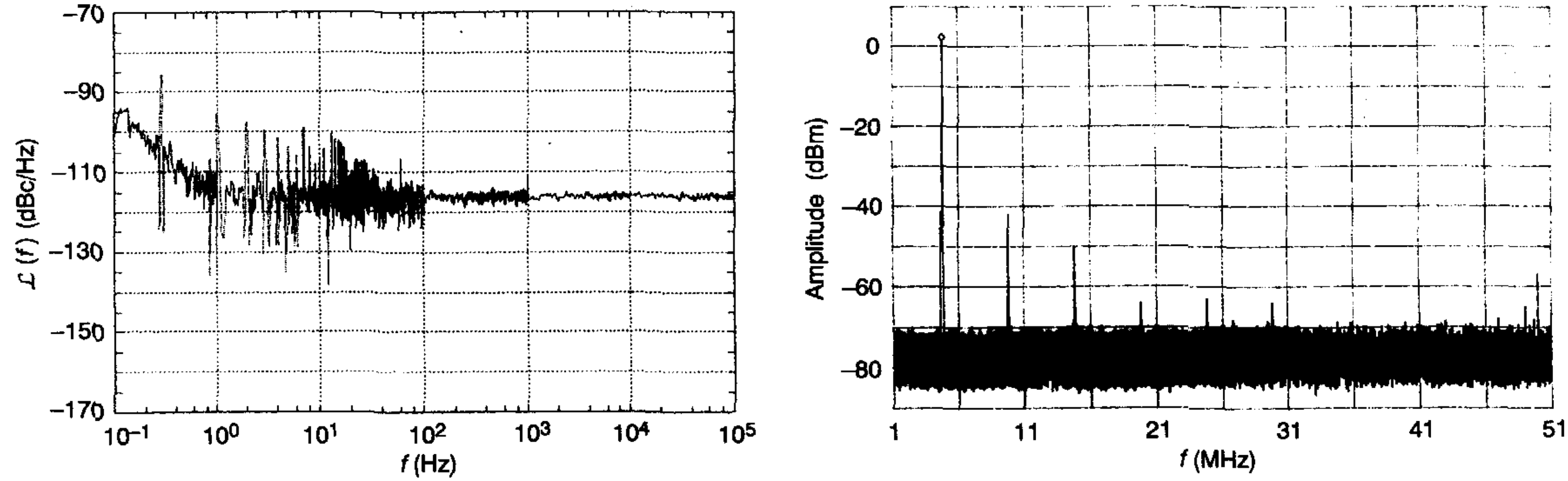
Figure 4. System C AM noise.



a. Single-sideband phase noise.

b. Output frequency spectrum.

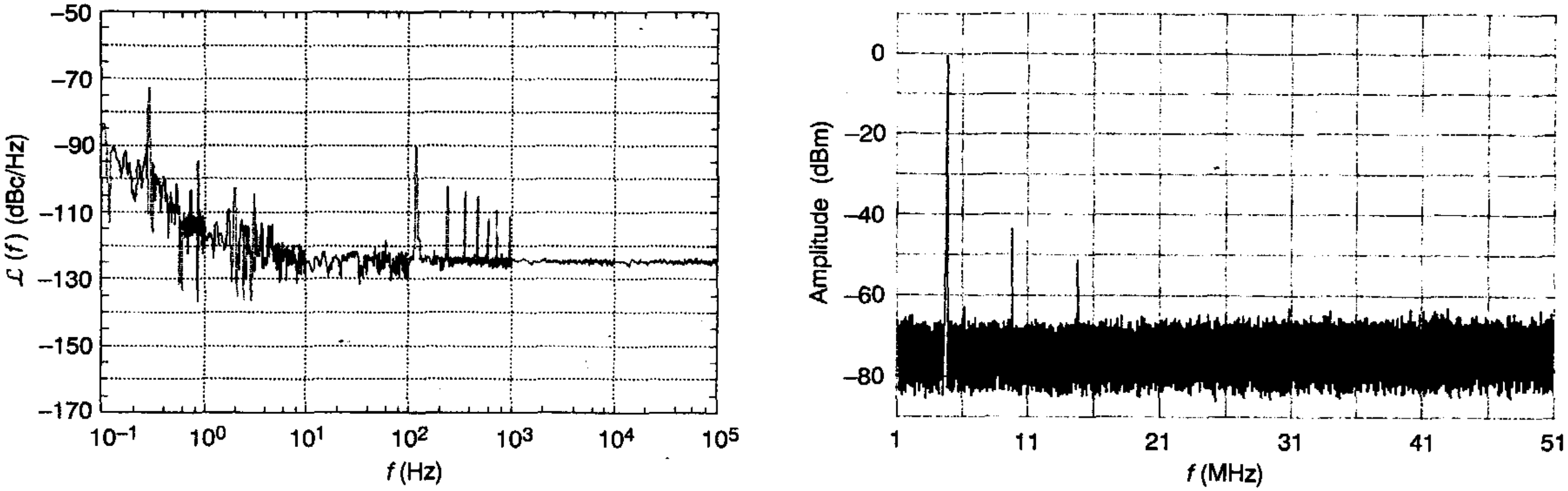
Figure 5. System A performance.



a. Single-sideband phase noise.

b. Output frequency spectrum.

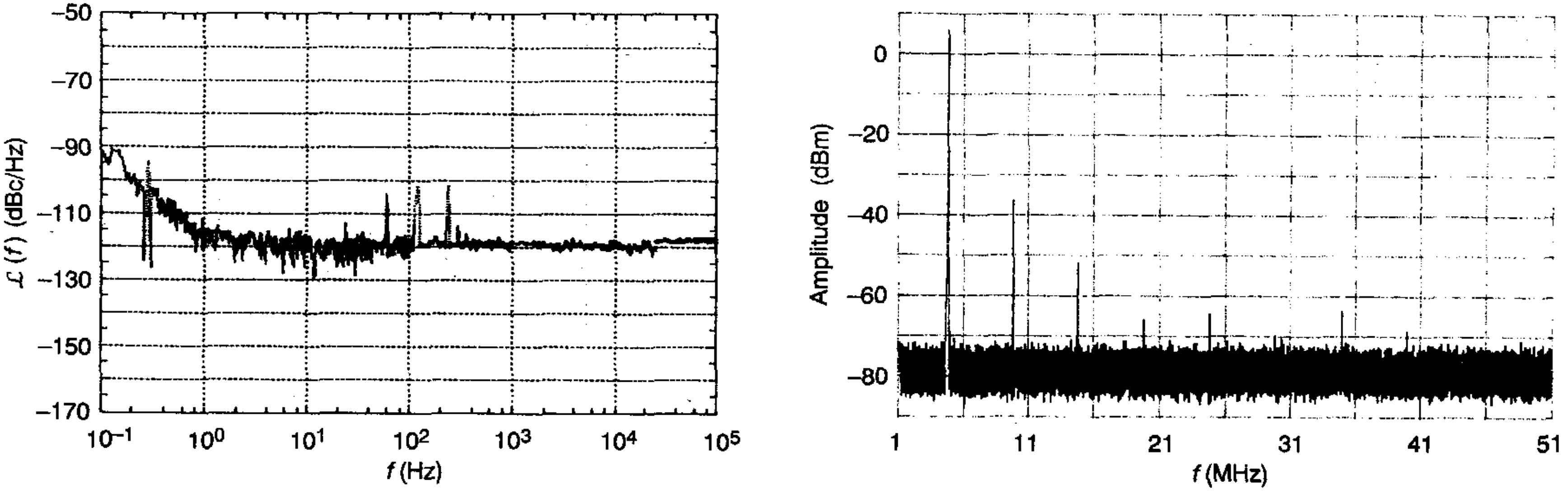
Figure 6. System B performance.



a. **Single-sideband phase noise.**

b. **Output frequency spectrum.**

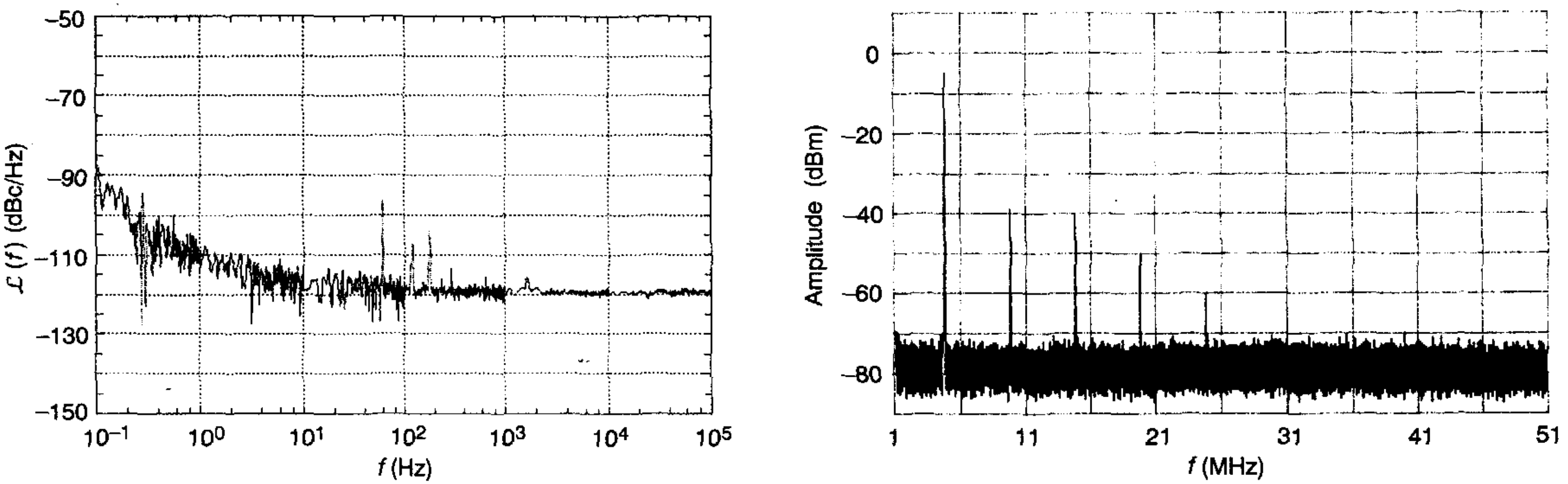
Figure 7. System C performance.



a. **Single-sideband phase noise.**

b. **Output frequency spectrum.**

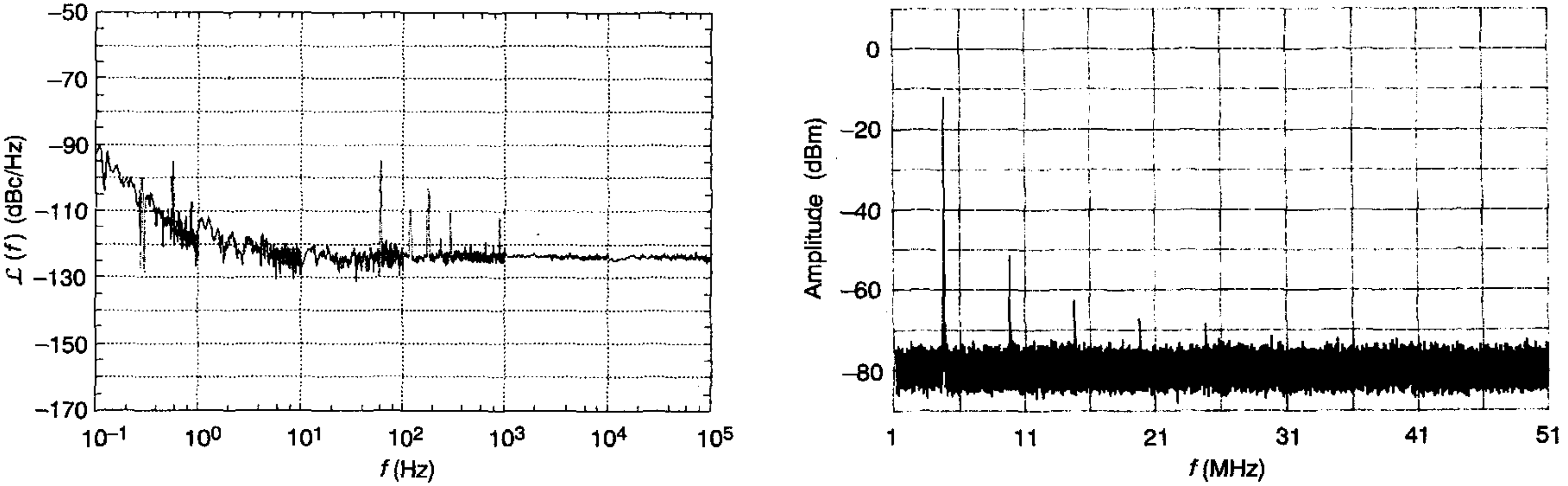
Figure 8. System D performance.



a. **Single-sideband phase noise.**

b. **Output frequency spectrum.**

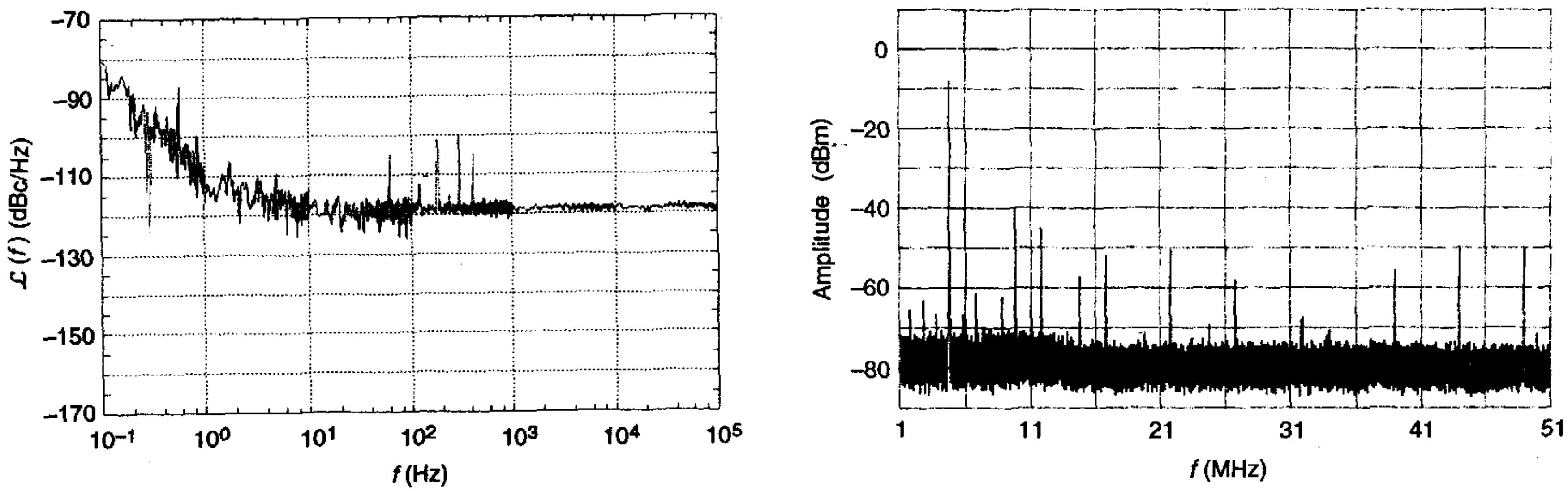
Figure 9. **System E performance.**



a. **Single-sideband phase noise.**

b. **Output frequency spectrum.**

Figure 10. **System F performance.**



a. **Single-sideband phase noise.**

b. **Output frequency spectrum.**

Figure 11. System G performance.

QUESTIONS AND ANSWERS

Question: In many cases it's a noise performance characteristic which is not only parameter of interest and have you also checked the delay stability for example with dependence on

Answer: We didn't do that in this particular test because our particular application is to use as a frequency reference, we're not really worried about the delay so much between the start and stop as we are as just a clean signal for for the user. It's also because these systems were demo and some of the demos were borrowed systems so I didn't have a good underground insulation to test a lot of the good thermal chamber to test temperature fluctuations. So no we didn't do this test.

Bill Riley, EG&G: It would seem that one of the advantages of using the fiber optic distribution would be to avoid hum. That wasn't really apparent in your data, I assume that most of those power lines spurs were from the measuring system but could you comment on the effectiveness of that length to avoid hum contamination?

Answer: Yes, that was the primary reason we sort of go into these systems because some of our clocks and lines where you could see 60 Hz superimposed on the signals, and the fiber optics obviously are immune to that but the problem you have to be careful of is that the receivers and transmitters aren't immune so you have to watch the chassis. The spikes and the plots were due to the phase and measuring system because it's plugged into a 60 Hz power supply so of course it's got hum. But the system is very effective in illuminating that cause the same we basically have parallel lines of coax and the fiber and the coaxial lines are essentially useless because there is almost as much 60 Hz as there was 5 MHz. And when we replace the same lines we're into the same conduits with these fibers and these transmitters. The signals are now you know they are fine, they're useable in the automatic about two years of use. They perform admirably. So they are definitely good for illuminating that as long as you keep your transmitter power supplies isolated from 60 Hz noise.