STATUS OF FREQUENCY AND TIMING REFERENCE SIGNAL TRANSMISSION BY FIBER OPTICS[*]

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Abstract

This paper will report recent progress in high stability fiber optic distribution of frequency and timing reference signals. It will give today's state-of-the-art performance at 100 MHz, 1 GHz, and 8.4 GHz for these systems. It will also describe system hardware and discuss cost-performance tradeoffs and future developments.

Introduction

State-of-the-art frequency standards provide accurate and stable frequency and time references needed for location and navigation of distant spacecraft and for precise geographic and geodynamic measurements using Very Long Baseline Interferometry (VLBI), and Connected Element Interferometry (CEI).

The high cost of frequency standards makes it impractical to provide one for each user at a complex. The alternative is to distribute the reference signal generated by a centrally located frequency and timing standard facility to all of the users in a complex.

Over the last two decades engineers have tried, using various technologies and schemes, to develop a means for high stability transmission of frequency references over distances up to a few tens of kilometers[1-4]. For various reasons, none of the technologies were found to be practical until the introduction of fiber optics in the late 1970's.

Since its introduction much progress has been made in the development of high stability analog fiber optic frequency reference distribution systems. Previous papers have reported on past progress in the development of these systems[5-10]. This paper will bring the user community up to date on recent developments.

For comparison, this paper will give the performance of a 1986 fiber optic frequency reference distribution system and the performance of today's state-of-the-art systems. It will also describe a lower cost, lower performance distribution system for the user who does not need full H-maser stability. Finally, the paper will discuss future fiber optic system developments and their potential impact on systems which use high stability frequency reference distribution.

Progress In Fiber Optic Frequency Reference Distribution

Fig. 1 is a block diagram of a typical fiber optic transmitter to be used for high stability applications, such as transmission of reference frequency signals. An electrical signal is applied to the input of the transmitter module where it is added to a constant bias current flowing through the semiconductor laser. The resultant time varying current in the laser diode generates an amplitude modulated (AM) optical signal. This optical signal, emitted by the laser, passes through an integral optical isolator (not shown) which is contained in the transmitter module and then through an optical fiber to an external optical isolator.

From the external isolator the signal passes through a variable optical attenuator which limits the optical output power. This attenuator is needed in short links because the output power of some transmitters may exceed the damage threshold of the receiver. The optical signal having passed through the variable optical attenuator enters another optical fiber and then passes through an optical bulkhead connector and into a fiber optic cable which carries it to the receiver.

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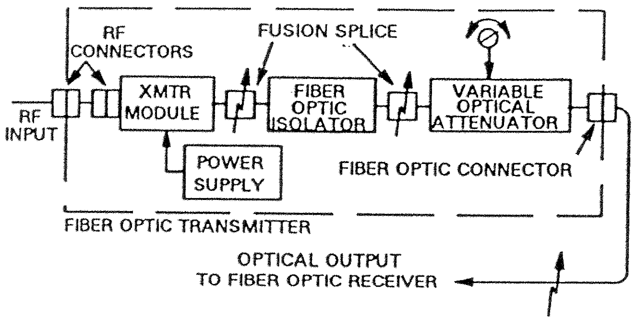

Figure 1. Block diagram of a state-of-the-art analog fiber optic transmitter.

Fig. 2 is a block diagram of a typical fiber optic receiver. The optical signal from the fiber optic transmitter enters the receiver module through a fiber optic bulkhead connector and an optical fiber pigtail. In the receiver module the optical signal is applied to a photodiode detector which converts it back to an electrical signal which is a reproduction of the electrical signal applied to the input of the optical transmitter.

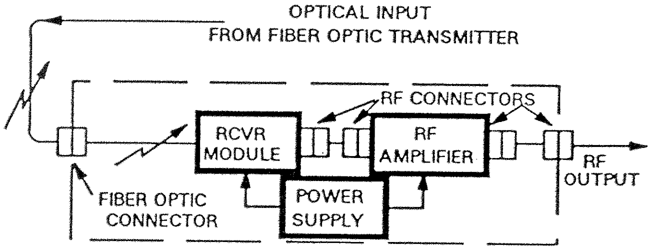

Figure 2. Block diagram of an analog fiber optic receiver.

The electrical signal thus recovered is amplified in an amplifier internal to the receiver module, an external amplifier, or a combination of internal and external amplifiers. In the best optical receivers there is a matching network between the photodiode detector and an internal amplifier. The matching network in effect lowers the equivalent input thermal noise floor of the receiver. The gain of the internal amplifier is chosen such that it will not saturate when large optical signals are applied to the receivers input. For optical signals smaller than the maximum signal an additional external amplifier is needed. The gain of this external amplifier is often adjustable to compensate for various input optical signal levels.

Figure 3 gives the results of measurements of differential frequency stability of a 1986 vintage fiber optic frequency reference distribution link tested over a 14 km distance.

The differential stability of this link was 1×10^{-15} for 1,000 seconds averaging time, about the same as the stability of a reference signal generated by a H-maser frequency standard[11]. However, the differential frequency stability of the 14 km fiber optic link for 1 second averaging time was about 4 times worse than a H-maser signal for the same averaging time because of inadequate Signal-to-Noise Ratio (SNR) resulting from signal loss over this long distance. When the link length was reduced to 10 meters the SNR improved resulting in improved short term frequency stability about 1.7 times better than a H-maser signal for 1 second averaging time.

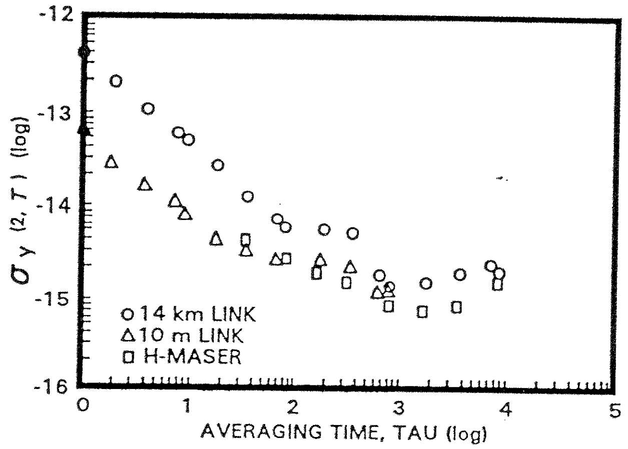

Figure 3. The Allan deviation of a 1986 vintage analog fiber optic link.

The degradation to a H-maser frequency reference signal transmitted over 14 kms with this 1986 vintage fiber optic link was small when the output signal was filtered with a phase locked loop having a 1 Hz bandwidth.

Close-to-carrier (CTC) phase noise was found to be inconsistent in these early analog fiber optic links. This problem was traced to optical reflections in the link from various sources. If reflected light was permitted to enter the laser it resulted in increased (CTC) phase noise as well as increased amplitude noise. Reflections as low as -100 dBmo entering the laser can increase the CTC phase noise.

The abbreviation dBmo refers to optical power level relative to 1 milliwatt, and dBme refers to electrical power level relative to 1 milliwatt. Likewise, dBo is an optical power ratio and dBe is an electrical power ratio.

Prior to 1989 manufacturers of lasers for analog fiber optic systems attempted to minimize noise resulting from reflections by reducing optical reflections from connectors and other components to less than -60 dBo. Measurements made at JPL proved this to be inadequate for some systems requiring very low CTC phase noise, such as those used for reference frequency distribution. Some manufacturers, responding to the needs of users, began to install integral optical isolators in their laser packages in 1989. Today lasers with integral optical isolators having >30 dBo isolation are the norm for amplitude modulated analog fiber optic systems.

Even though lasers with integral optical isolators improved the laser noise considerably, the 30 dBo isolation they provide is still not adequate for critical applications. An additional external optical isolator having >30 dBo isolation and very low back reflection, <-65 dBo, is needed to achieve the lowest CTC phase noise.

Fig. 4 is a plot of double sideband CTC phase noise versus frequency as a function of reflected optical power into a semiconductor laser transmitter with an integral optical isolator having 30 dBo isolation. The optical power entering the laser itself when a -34.5 dBmo reflection is present is only -64.5 dBmo. The lower line is the measured phase noise when reflections were reduced to a level where further reduction had no effect on the CTC phase noise.

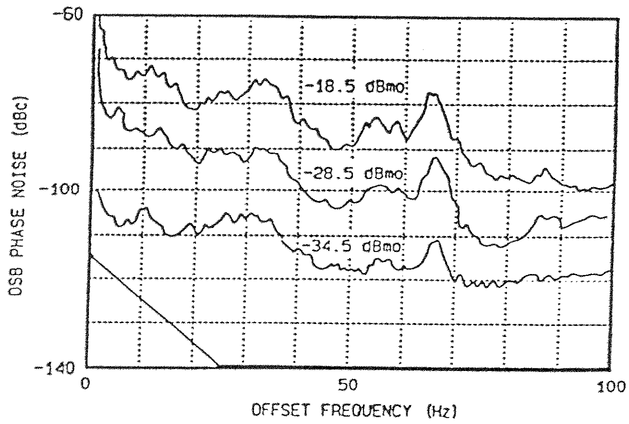

Figure 4. Analog fiber optic link phase noise versus reflected optical power.

Furthermore, it was found that reflections from surfaces internal to the laser package also resulted in increased CTC phase noise. This CTC phase noise is generated by interference fringes which occur in the cavity consisting of the external surface of the laser and the surface of the coupling lens when the laser frequency varies with temperature.

In Fig. 5, a plot of relative group delay in a fiber optic link versus laser diode temperature shows the result of this effect. The cyclical variation is due to reflections internal to the laser package. Based on these findings the suggestions shown in Fig. 6 to reduce CTC phase noise due to these effects were made[12].

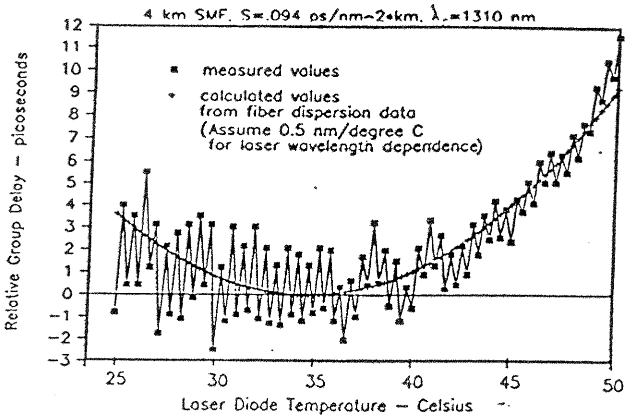

Figure 5. Group delay versus laser diode temperature for a 4 km analog fiber optic link.

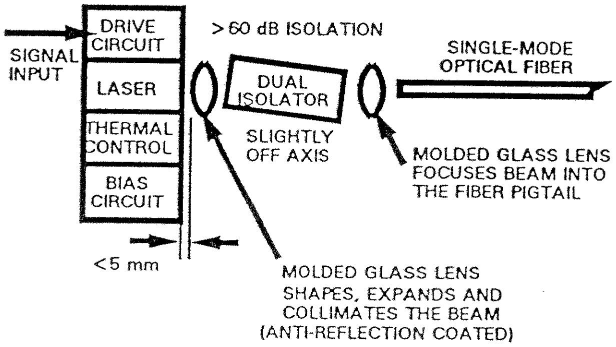

Figure 6. Suggested packaging for an analog fiber optic transmitter.

After this information was reported, Ortel Corporation of Alhambra, California developed a proprietary technique to reduced internal reflections to a very low < -90 dBmo. This substantially reduced CTC phase noise from this source in their transmitters.

In fiber optic systems using narrow linewidth laser sources multiple reflections in the optical fiber also generate increased CTC phase noise. The cause of this noise is interference between the forward signal and reflections propagating in the forward direction. In these systems optical reflections must be kept to a minimum even if the laser is highly isolated[13].

Ortel Corporation has incorporated low internal reflection and an integral optical isolator into both a low frequency distributed feedback (DFB) laser and a microwave Fabry-Perot semiconductor laser. The DFB laser can be directly modulated up to 1 GHz and the Fabry-Perot laser can be directly modulated at frequencies as high as 12 GHz.

The results of phase noise measurements made at JPL on fiber optic systems using these improved fiber optic transmitters are compared, in Fig. 7, to various frequency sources. The phase noise shown for a fiber optic system using the DFB laser was measured at 100 MHz and normalized to 8.4 GHz. The phase noise shown for a fiber optic system using the Fabry-Perot laser was measured at 8.4 GHz.

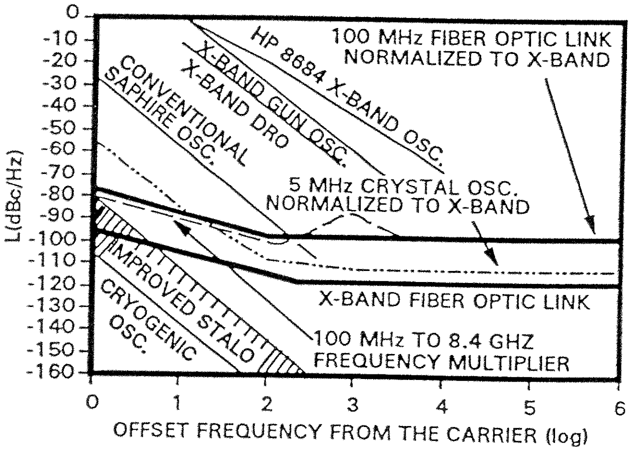

Figure 7. Phase noise of state-of-the-art fiber optic links relative to various frequency sources and a good frequency multiplier.

The Allan deviation for state-of-the-art fiber optic links is shown in Fig. 8. At 100 MHz the measurements were made on a fiber optic link using a DFB laser of the type described above. At 1 GHz and at 8.4 GHz the measurements were made on a fiber optic link using the Fabry-Perot laser described above. The short term Allan deviations shown for these fiber optic systems were calculated from phase noise measurements because the Allan deviations are below the noise floor of existing Allan deviation measurement systems.

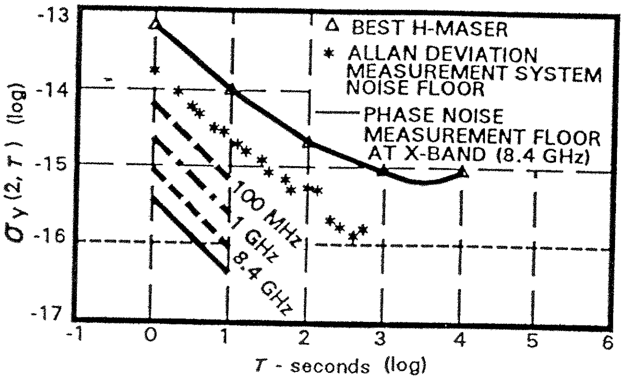

Figure 8. Allan deviation for state-of-the-art fiber optic links at 100 MHz, 1 GHz, and 8.4 GHz.

In most systems, for averaging times longer than a few tens of seconds, frequency instabilities due to thermal effects predominate. Cable delay variations resulting from thermal changes are the major contributor of instability for these averaging times. Low thermal coefficient of delay (0.1 ppm/°C) fiber optic cable, which has recently been developed, reduces cable group delay variations with temperature and greatly improves the long term frequency stability of fiber optic links exposed to large thermal variations[14].

Fiber optic cable stabilizers have been developed which can reduce instabilities below the level achievable with passive means. These stabilizers can virtually eliminate diurnal group delay variations in long analog fiber optic links used to transmit either narrow band reference frequency signals or wide band data signals[15].

A Cost Performance Tradeoff

Table 1 gives a cost breakdown of a state-of-the-art analog fiber optic system with 1 GHz modulation bandwidth which is suitable for applications such as frequency reference distribution. The prices given are small quantity prices and decrease rapidly with volume. The general price trend for this equipment is down. As sales volume picks up, over the next few years, the prices will be reduced drastically.

When these systems are used for frequency reference distribution a phase locked loop filter may be needed to improve short term phase noise. High quality commercial phased locked loop filters are available for about $10,000.

STATE-OF-THE-ART ANALOG FIBER OPTIC LINK

Name	Quantity	Price
Optical Transmitter Module	1	$12,545
Optical Receiver Module	1	5,495
Optical Isolator	1	1,650
Connectors	4	350
Bulkhead Adapters	2	60
Fiber Optic Cable Organizer Box	2	345
Variable Optical Attenuator	1	432
Enclosure	2	264
Amplifier	1	1,000
Transmitter Power Supply	1	326
Receiver Power Supply	1	140
Miscellaneous Parts		500
Subtotal		$23,107
Phase Locked Loop		$10,000
Grand Total		$33,107

HIGH QUALITY COMMERCIAL ANALOG FIBER OPTIC LINK

Fiber Optic Transmitter/Receiver Pair	$10,000
Phase Locked Loop	$10,000
Grand Total	$20,000

Table 1. A comparison of the price of a state-of-the-art analog fiber optic system to a commercial fiber optic television transmission system which can be adapted to transmitting 5 MHz frequency references having Cesium stability.

A commercial pulse frequency modulation system sold by Grass Valley Group, Grass Valley, California has been used, with a slight modification, at JPL and in the NASA Deep Space Network (DSN) for simultaneous transmission of a 5 MHz frequency reference and a time code signal[16]. Fig. 9 is a block diagram of this system. Its differential frequency stability (Allan deviation) when used with a clean-up loop is given in Fig. 10. Its phase noise is given in Fig. 11. The cost of this system is $20,000 including the fiber optic link and the phased locked loop filter.

As mentioned previously the optical power of some laser transmitters, when used in a short link, exceeds the maximum input optical power limit of the optical receiver. For links shorter than about 10 km this excess power can be used to reduce the cost of a transmission system by using a single transmitter to send a frequency reference signal to several locations. Such a distribution system is shown in Fig. 12.

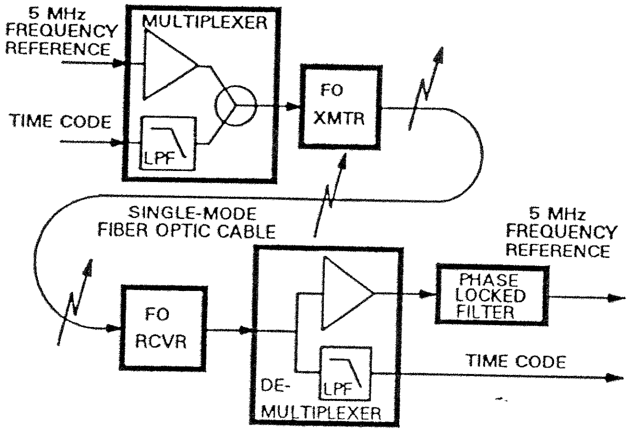

Figure 9. Block diagram of a frequency and timing system which uses a commercial fiber optic transmission system to transmit both a time code and a 5 MHz frequency reference.

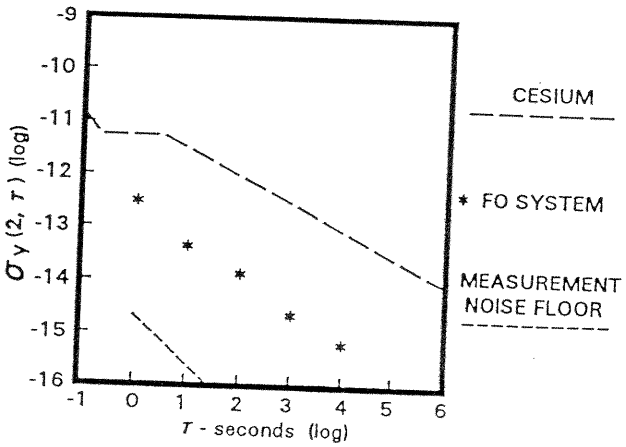

Figure 10. Allan deviation of the system shown in figure 9 compared to the Allan deviation of a Cesium frequency standard.

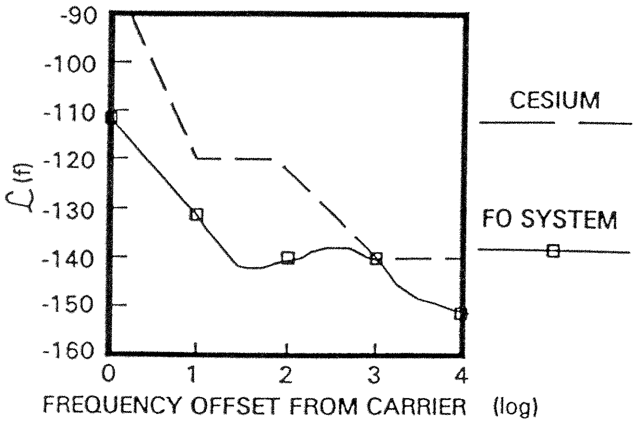

Figure 11. Phase noise of the system shown in figure 9 compared to the phase noise of a Cesium frequency standard.

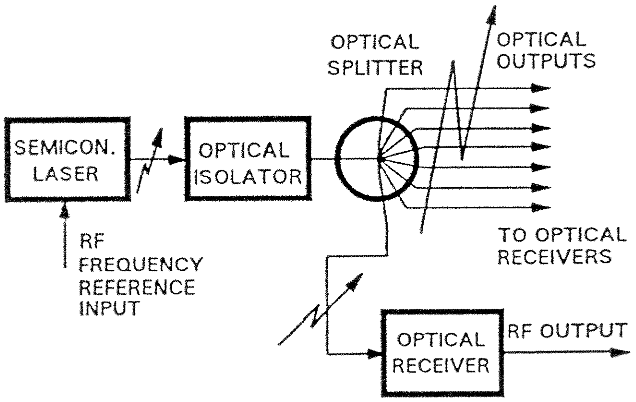

Figure 12. Block diagram showing the use of a single fiber optic transmitter to send a frequency reference to multiple users.

Future Improvements

Semiconductor lasers are predominately used to convert electrical signals to optical signals in today's digital and analog fiber optic transmission systems. The maximum SNR of these systems, about 140 dBe, is usually limited by laser noise. New systems are being developed which use optical transmitters consisting of semiconductor pumped solid state lasers, such as the Nd:YAG laser, with an external electro-optic modulator. These systems will have much higher optical output power and much lower noise.

Fig. 13 shows the optical power, detected RF power, shot noise power density, and thermal noise power density at the input to the receiver versus transmission distance for one of the new systems having +4 dBmo optical output power. Shot noise in this system predominates out to about 25 km. Without considering the effects of optical fiber nonlinearities, the SNR increases linearly with optical power in the shot noise limited region, as shown in Fig. 14.

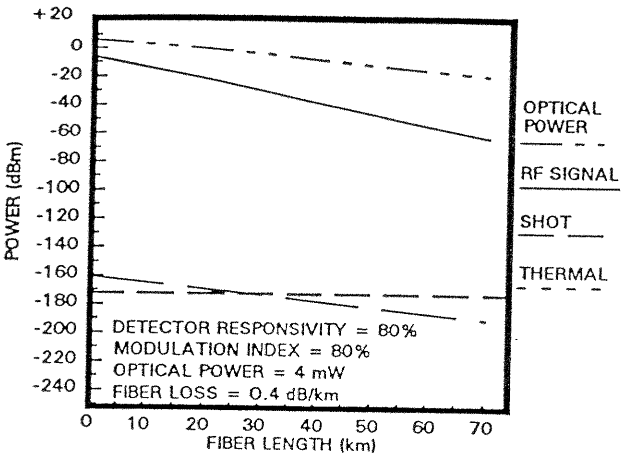

Figure 13. A plot of the predominate noise sources for advanced fiber optic systems now in development.

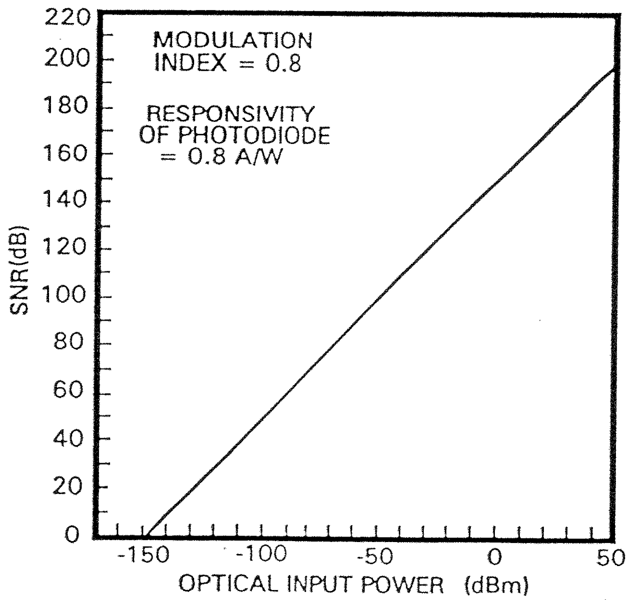

Figure 14. A plot of potential SNR versus optical power for advanced fiber optic links.

The potentially higher SNR of these new systems should result in improved phase noise of analog fiber optic transmission systems to the levels shown in Fig. 15.

Improvements in the 1/f noise region of these systems is uncertain because the mechanisms for this phase noise are not well understood. However, active feedback should give us considerable improvement in this region.

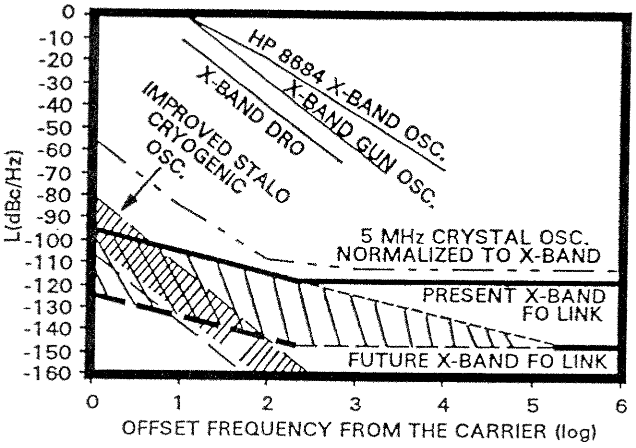

Figure 15. A plot showing the expected phase noise of advanced fiber optic links now in development compared to various frequency sources.

The high stability, dynamic range, and wide bandwidth of these advanced fiber optic systems, which are now in development, could eliminate the need to transmit reference frequencies more than a few feet. These fiber optic systems could transmit the RF and microwave signals directly from the front end of a receiver, for instance, to the vicinity of the frequency and time references for processing. Systems configured in this way will have better stability than those which transmit reference frequencies to a distant location and then send interfrequencies back to a central processing facility for processing.

Conclusion

Recent improvements in analog fiber optic system technology have resulted in substantial reduction of phase noise. The present state-of-the-art phase noise of these systems is -95 dBe, in a 1 Hz bandwidth, 1 Hz from a 8.4 GHz carrier. This is much better than the phase noise of any frequency standard in use today and approaches the phase noise of cryogenic frequency standards being developed[17].

A cost-performance tradeoff has been presented along with a cost savings suggestion to use a single fiber optic transmitter to transmit a signal to several users simultaneously.

The phase noise performance of future fiber optic systems which use a new optical transmitter technology has been predicted to be 25 dB better than today's state-of-the-art fiber optic systems.

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