

Analog fiber optic links for EMC emission testing

A sensitive, wideband, low-noise, analog fiber optic link can be used for EMC emission testing.

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An emission test is one of the most commonly performed EMC tests. This test usually involves low-level signals that cover a wide frequency range from kHz to many GHz.¹ A typical emission test setup consists of a test site at one end and some measurement instruments at the other, connected by a radio frequency and microwave transmission medium (Figure 1). This medium may be a length of cable, or a system consisting of a number of devices. It may also include control wires when remote control and automation are necessary. The distance between the test site and the instruments may range from a few meters to many kilometers. This requires high fidelity transmission of low-level, high bandwidth, RF/microwave signals over a long distance.

With the increasing demand for EMC tests, a growing need for such long distance links is expected. In particular, the EMC test community is asked to deliver efficient service through the use of automation, remote control and the sharing of measurement equipment.

At present, the commonly used transmission medium is coaxial cables. But RF/microwave signals suffer significant loss and distortion after going through a long coaxial cable. For example, the loss of RG-58U coaxial cable is specified at 100 MHz as 15 dB/100 meters.¹ The cable loss increases with the frequency, thereby severely limiting the bandwidth. In the past decade, fiber optic RF/microwave links have shown promise in replacing conventional RF/microwave transmission mediums, including the coaxial cable.²

BENEFITS OF USING FIBER OPTIC SYSTEMS

Fiber optic RF/microwave links significantly outperform conventional coaxial cables in many aspects. The key benefits

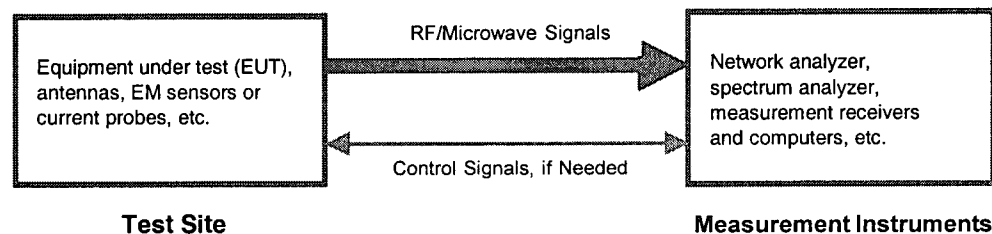


Figure 1. Emissions test setup showing test site, signal transmission medium and remote measurement instruments.

of a fiber optic link are:

- **Low Cable Loss**

The optical cable loss is less than 1 dB/km. This enables high fidelity signal transmission over a long distance.

- **High Bandwidth**

The high bandwidth is particularly beneficial as EMC tests move toward frequencies in excess of 1 GHz.

In addition, the optical fiber is physically small, flexible and lightweight. The inherent immunity of optical fibers to electromagnetic interference makes them attractive

where ambient RF and microwave signals are present.

ANALOG FIBER OPTIC LINK

The technique of transmitting RF/microwave signals over a fiber optic link requires that the signals be applied to an optical modulator. The intensity modulated optical carrier is then transmitted over an optical fiber. At the receiver, the optical signal is demodulated using a photodetector.

There are two ways to modulate the optical carrier—direct modulation and external modulation. Both

techniques generally result in a link with a high noise figure. However, by employing a low noise laser source and including low noise gain stages in the link, the system noise floor can be reduced to acceptable levels so as not to degrade the measurement sensitivity.

DIRECT MODULATION

In the direct modulation approach, the microwave signal produced by the field probe modulates the laser diode drive current to produce an intensity modulated optical carrier (Figure 2). Thus, the microwave signal is impressed on the laser carrier that is then coupled to a fiber optic link.

EXTERNAL MODULATION

External modulation uses external electro-optic modulators to transpose the microwave signals onto the optical carrier. The modulator operates on the principle of the electro-optic effect that causes a phase change in the optical signal propagating in the electro-optic substrate material. The phase modulation is converted to optical intensity modulation by interference of light in an intensity modulator, such as the integrated optic Mach-Zehnder interferometer (Figure 3). A fiber optic link based on such an intensity modulator is also shown (Figure 4).

ADVANTAGES OF

EXTERNAL MODULATION

External modulation offers a number of advantages over direct modulation:

- Electro-optic modulators overcome the bandwidth limiting effects of laser chirps introduced by direct modulation of laser diodes. Presently, at frequencies higher than 15 GHz, only external modulation systems can satisfy the performance needs.
- Electro-optic modulators have a higher damage threshold compared to electrically sensitive and delicate laser diodes.
- Laser diodes require a significant amount of electrical power to pro-

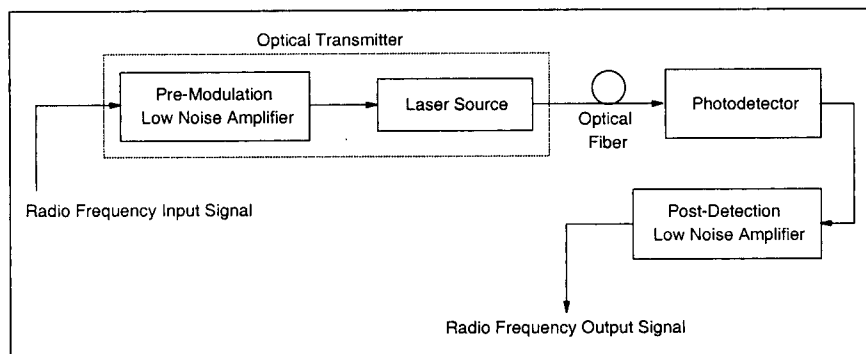


Figure 2. Fiber optic link based on direct intensity modulation of a laser diode.

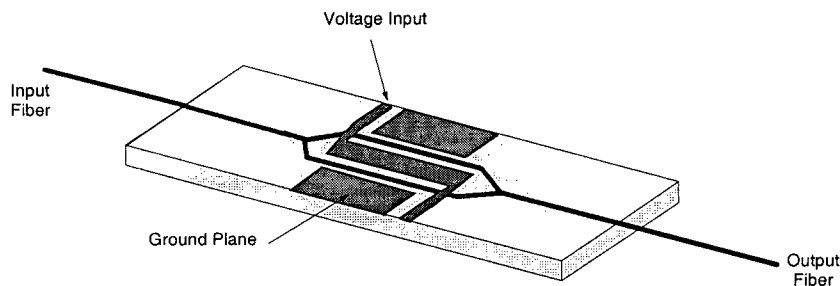


Figure 3. External optical intensity modulator based on an integrated optic Mach-Zehnder interferometer.

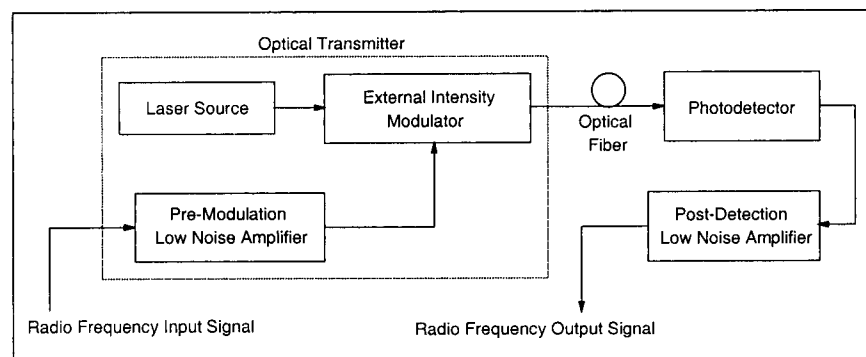


Figure 4. Fiber optic link based on external intensity modulation of an unmodulated laser carrier.

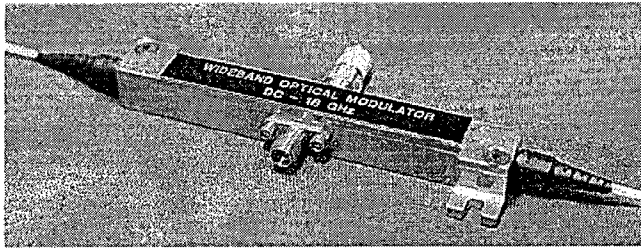


Figure 5. A wideband integrated optic intensity modulator that can be used for external modulation.

duce the drive current and to operate the temperature controllers.

- Directly modulated lasers are generally noisier than unmodulated lasers, so that external modulation systems have the potential for lower noise figures.
- Finally, in less demanding applications, where the noise figure is not such an important issue, the completely passive nature of the external modulator may hold significant benefits. By eliminating the pre-modulation low noise amplifier (LNA), no electrical power is required at the modulator other than that provided by the modulating signal. Thus, the full benefits of the electrical isolation of fiber optics can be exploited and completely passive remote antenna applications become possible.

For these reasons, external modulation is often used in fiber optic links (Figure 5). In order to obtain the lowest noise floor and the highest dynamic range, the microwave signal is fed into a pre-modulation amplifier and applied to the optical intensity modulator. The modulated optical signal is sent to the fiber cable and demodulated by the photodetector at the other end. Before leaving the system, the signal is further amplified by a post-detection amplifier to overcome the kT thermal noise of the user's signal processing system. The key system performance specifications are:

- Noise Figure < 7dB
- Instantaneous Dynamic Range > 60 dB in 1 MHz
- Frequency Range: 10 kHz to 3 GHz

SYSTEM ANALYSIS FOR EXTERNAL MODULATION LINKS

This section discusses the parameters that determine the performance of the optical link. Special attention is paid to the analysis of system noise and an implementation scheme to reduce the system noise figure, to satisfy even the most demanding EMC test requirements. Wideband optical links usually have relatively high system noise levels due to one or more of the following major causes: laser relative intensity noise (RIN), optical receiver sensitivity and small modulation depth.

Laser Relative Intensity Noise. In order to achieve the highest dynamic range for the fiber optic link, the excess laser intensity noise, if it exists, must be substantially suppressed. Low noise sources such as solid-state

Nd:YAG lasers or distributed feedback (DFB) semiconductor lasers are ideal for maximizing the sensitivity and dynamic range of a fiber optic microwave transmission system. Preferred laser wavelengths are 1300 nm and 1550 nm, where the optical loss and dispersion in fibers are low.

Optical Receiver Sensitivity. Wideband photodetectors require a high optical power to achieve shot-noise-limited detection to maximize sensitivity and dynamic range. However, high bandwidth photodetectors saturate before reaching the shot-noise condition, thus reducing the available dynamic range. This occurs because a small active area is used for these photodetectors to minimize the RC time-constant. Because of the quantized nature of light, there is a "quantum" noise component associated with the statistical arrival of photons that is not observed at microwave frequencies. To maximize the sensitivity of an optical receiver, the optical power at the receiver must be sufficient to produce what is called "quantum noise-limited detection." The sensitivity and dynamic range could be extended when higher saturation power, high bandwidth photodiodes become commercially available.

Modulation Depth. The optical modulation depth is kept to less than 10% to avoid non-linearities and distortion. Pre-distortion of the modulating signal is one technique that could be used to increase the linear modulation depth and, thus, improve the dynamic range.

Bandwidth. Large instantaneous post-detection bandwidth greater than 1 GHz requires small photodetector loads, i.e., 50 ohms. This produces a high threshold for quantum noise-limited detection and this imposes severe constraints on the sensitivity of wideband systems.

The greatest challenge in the design of the fiber optic microwave system is to minimize the overall system noise figure while working within the above mentioned constraints. The following sections derive several key system performance specifications.

INTENSITY MODULATOR TRANSFER CHARACTERISTIC

The output of an integrated optic intensity modulator biased in its linear region is given by:

$$P_o = P_i \cos^2\left(\frac{\Delta\Phi}{2} + \frac{\pi}{2}\right) \quad (1)$$

where P_i is the optical power input, P_o is the optical output power at the photodetector and $\Delta\Phi$ is the phase modulation depth. The output intensity of this modulator follows a cosine-squared function which is characteristic of interferometers (Figure 6). Because of the cosine-squared transfer characteristics, the modulation depth is limited to less than about 10% for linear operation.

The small modulation depth limits the available dynamic range. Therefore, it is very important to optimize the pre-modulation and post-detection stages in order to prevent further reduction in dynamic range.

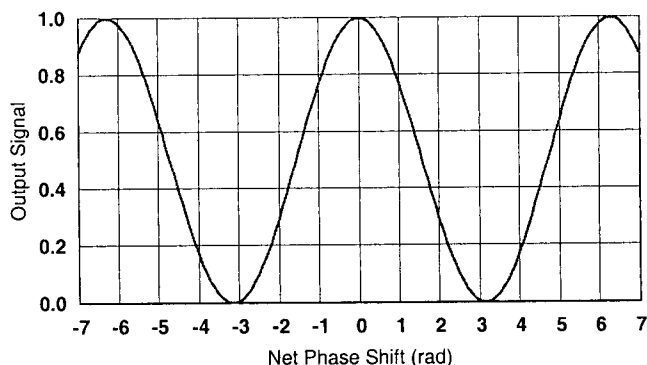


Figure 6. Cosine-squared transfer function of an external optical intensity modulator based on a Mach-Zehnder Interferometer.

CARRIER-TO-NOISE RATIO (CNR)

In a direct detection optical link, the CNR for a substantially quantum noise-limited receiver is given by:

$$\text{CNR} = \frac{\eta P_o}{2hf_o B_n} \quad (2)$$

where

η = quantum efficiency (0.6)

e = electronic charge (1.6×10^{-19} C)

P_o = mean optical power at the photodetector (1 mW)

h = Planck's constant (6.63×10^{-34} J.s)

f_o = frequency (2.31×10^{14} Hz)

B_n = noise equivalent bandwidth (1 MHz)

The corresponding CNR is 92.9 dB re 1 MHz bandwidth. It can be shown that the 1 mW of optical carrier power is insufficient for quantum noise-limited detection in this receiver, and the CNR is degraded by 6.3 dB, leaving a resulting CNR = 86.6 dB re 1 MHz. This degradation is unavoidable because of the limited power handling capability of high-speed photodetectors. To avoid further degradation in CNR, the effective noise figure of the post-detection receiving system must be minimized.

SIGNAL-TO-NOISE RATIO (SNR)

A key parameter of an integrated optical circuit (IOC) modulator is V_π , which is the voltage required to produce a π radian phase shift. If we assume a V_π of 15 volts, the transfer coefficient of such a wideband IOC modulator is π/V_π , or 0.21 radians per volt. Because the transfer function has a cosine-square characteristic, typically, the modulation depth is restricted to about 0.1 to 0.2 radians to avoid non-linear distortion products. The 1-dB compression level occurs at a deviation of 0.95 radians.

For small phase deviations in the linear region of the bias curve, the SNR is given by:

$$\text{SNR} = \text{CNR} \frac{\Delta\Phi^2}{2} \quad (3)$$

Using the previous values of the parameters, and for

a maximum linear phase modulation depth $\Delta\Phi = 0.2$ radian, Equation 3 shows that the SNR = $86.6 - 17 = 69.6$ dB re 1 MHz.

The intensity modulation is linear up to a phase deviation of about 0.2 radians, corresponding to a maximum drive voltage for linear operation of 0.95 volts. The electrical input power into the 50-ohm integrated optic modulator required to produce this deviation is +9.6 dBm. It can be shown that the corresponding electrical output signal from the photodetector is -40.1 dBm. Thus, the electrical conversion loss through the system is about 50 dB. Expressed in another way, we can say that the link gain ≈ -50 dB. This also corresponds to the noise figure of the link. To compensate for this high noise figure, LNAs are included between the RF signal source and the modulator. Alternatively, we can lower the V_π of the modulator to increase the link gain and thus reduce the noise figure.

EXPERIMENTAL DEMONSTRATION OF LOW SYSTEM NOISE FIGURE

EMC emission test conditions demand the most sensitive system configuration. A pre-detection amplifier with a low noise figure and high gain is required to compensate for the intrinsic high noise figure of the intensity modulator. Similarly, to compensate for the high noise figure of the test instrumentation, a post-detection amplifier with low noise figure and high gain is also required. Assuming the test instrumentation has a noise figure of 40 dB, a gain of about 50 dB is required to substantially reduce the total noise figure. Obviously, different link sensitivities can be achieved through optimization of the pre-detection and the post-detection amplification. The 40-dB instrumentation noise figure is typical for most microwave spectrum analyzers in the frequency region of 18 GHz. There are, however, many instruments on the market with lower noise figures.

The performance of the fiber optic link has been experimentally confirmed. Without the amplifiers, the measured overall system noise figure was equal to 43.7 dB. With the amplifiers, the system noise figure fell to 4.1 dB. A system noise figure of 2.9 dB has been measured at 800 MHz (Figure 7).

Thus, it is possible to produce optical links with noise figures close to 3 dB. There is considerable interest in the photonics industry to further lower the intensity modulator V_π so that the noise figure can be reduced without resorting to high levels of pre-modulation gain. Work is underway in the industry to drive the V_π to as low as 1 volt. This would improve the passive link gain example shown here by 23.5 dB so that noise figures for links with passive modulators, i.e., those without pre-modulation LNAs, could fall to about 26 dB. As implied earlier, the passive noise figure could be further lowered by employing state-of-the-art photodetectors with higher optical saturation power limits.

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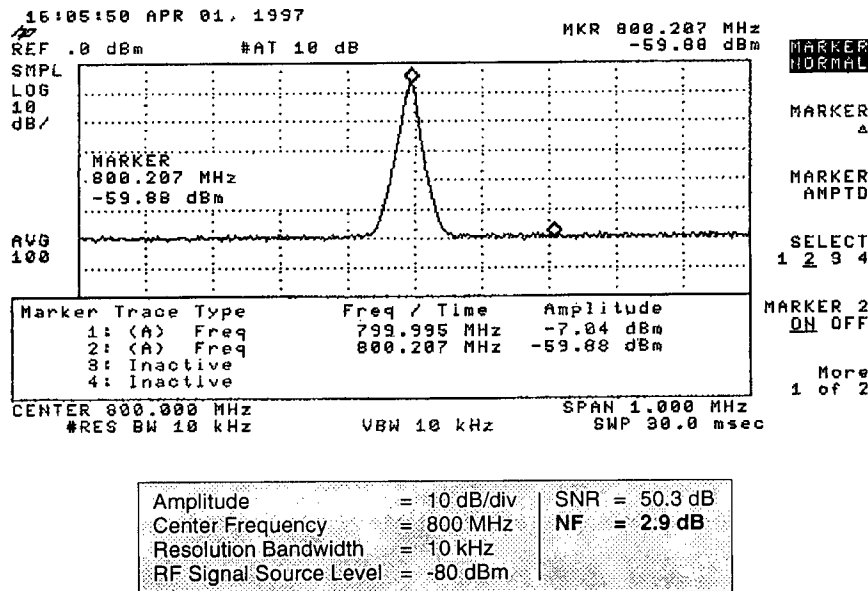


Figure 7. Performance of a low-noise fiber optic link using an external intensity modulator. Spectrum shows the sensitivity obtained by employing low-noise LNAs to provide both pre-modulation and post-detection amplification. RF input to modulator terminated by a 50-ohm impedance.

AN EXAMPLE OF EMC EMISSION TEST SYSTEM USING THE FIBER OPTIC LINK

Figure 8 illustrates an example of an EMC radiated emission setup using a RF/microwave fiber optic link. The EUT is located at an open field test site, which may be over 100 meters away from the measurement and control room.

Suppose that at 10 meters from the EUT, the antenna measures a RF field of 70.8 $\mu\text{V/m}$ at a frequency of 1 GHz—a radiated limit set by CISPR 22. With an antenna factor of 15 dB (m^{-1}), the input level into the fiber optic link would be 12.6 μV , or -88 dBm for a 50-ohm system. If a high-

sensitivity fiber optic link producing an overall system noise figure of 4 dB is employed, the signal would be measured with an SNR of 22 dB with respect to a 1-MHz bandwidth. The link would have an instantaneous linear dynamic range of greater than 60 dB re 1-MHz bandwidth. Properly configured, this type of fiber optic link is thus capable of being “transparent” to the user and will not degrade the sensitivity and quality of EMC test measurements.

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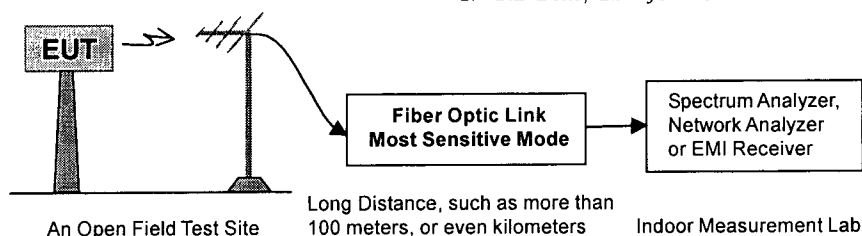


Figure 8. The schematic shows a radiated emission measurement test setup, employing a fiber optic link for signal transmission.

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