

Sensitivity Enhancements to Photonic Electric Field Sensor

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ABSTRACT

This paper describes an electrode-less, all-optical, wideband electric field sensor fabricated in an electro-optic lithium niobate substrate. The sensor component is an integrated optic Mach-Zehnder interferometer. The electric field sensor uses the electro-optic properties of lithium niobate to modulate the phase of the light propagating in each arm of the Mach-Zehnder interferometer. The phase modulated light is then converted to intensity modulation at the output of the interferometer. The unique feature of the sensor device is that the orientation of the crystal in one arm of the Mach-Zehnder interferometer is inverted to provide push-pull optical modulation for an applied electric field. Optical fibers are connected to the input and output of the sensor device. The basic device is an all-dielectric intensity modulator. The ability to operate the sensor without the use of any metal antenna permits its use in extremely high field conditions without any danger of damaging the sensor. The optical fiber connections provide optical isolation to the instrumentation to protect the instrumentation from possible overload conditions. The electrode-less sensor is designed specially for measuring high field strengths similar to the conditions in electromagnetic pulse, high power microwave and high voltage power lines. Sensitivity improvements are possible by using carrier suppression techniques.

Keywords: lithium niobate, ferroelectric, electro-optic, fiber optic, optical modulator, waveguide, Mach-Zehnder, domain inversion, carrier suppression

1. INTRODUCTION

The novel all-optical electric field sensor uses fiber and integrated optics technologies. One unique advantage of this sensor is that it eliminates the use of metallic antenna or electrical connections that can interfere with the accurate measurement and characterization of the EM environment. Because the electric field sensor is an all-optical and an all-dielectric device, it offers minimal disturbance to the electric field to be measured.¹

The sensor system uses a laser whose output is provided as input to the photonic electric field sensor. The electric field sensor is placed in the EM environment. The optical output of the sensor is modulated by the electric field present in the EM environment. The optical output, which is a linear representation of the electric field present in the EM environment, is provided to an optical fiber. The output optical fiber is connected to a detection system consisting of an optical receiver and low-noise preamplifiers. The RF output of the detection system is processed and recorded as needed.

The fabricated electric field sensor component, shown in Figure 1, is a novel all-optical device that uses fiber and integrated optics technologies. The sensor is packaged with optical fibers for input and output. The optical fibers enable remote measurement of the field from a safe distance of 100 meters. The small size and ruggedness of the device is made possible by the successful formation of an integrated version of a Mach-Zehnder interferometer, a particular optical interferometer configuration.² The Mach-Zehnder interferometer is fabricated in an electro-optically active lithium niobate crystal substrate using the technologies of integrated optics. The electric field sensor uses the electro-optic properties of lithium niobate to phase modulate the light propagating in each arm of the Mach-Zehnder interferometer. This phase modulated optical signal is converted to intensity modulation at the output of the interferometer.

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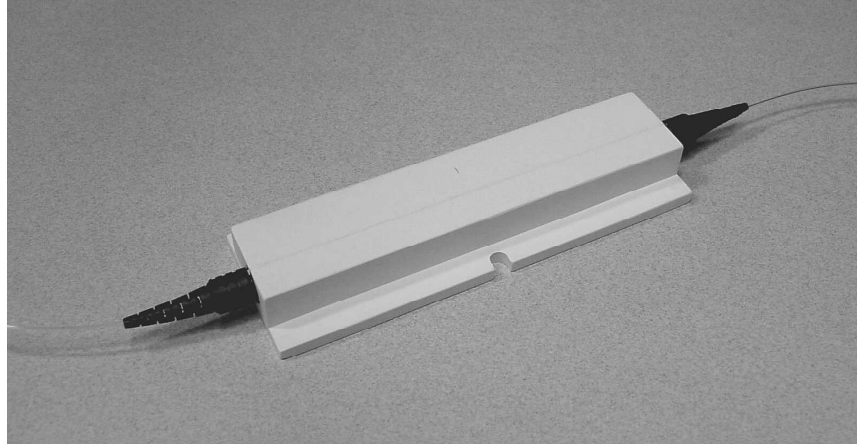


Figure 1. Photograph of a prototype photonic electric field sensor

2. MACH-ZEHNDER INTERFEROMETER ELECTRIC FIELD SENSOR

A schematic of the electric field sensor configuration is shown in Figure 2. The optical waveguide circuit is a Mach-Zehnder interferometer consisting of a reverse-poled region in one of the waveguide channels. This device structure has input and output Y-branches. Light input to the sensor is received from a polarization maintaining single mode fiber. Light output from the sensor is connected to a standard single mode fiber.

The applied electric field produces equal and opposite phase shifts in the optical beam propagating in the two channels, thereby leading to a net phase shift of twice the phase shift per channel. When the two optical beams recombine at the output Y-branch, the phase modulation is converted to an amplitude-modulated signal at the same frequency of the external electric field. The optical signal amplitude is proportional to the applied electric field.

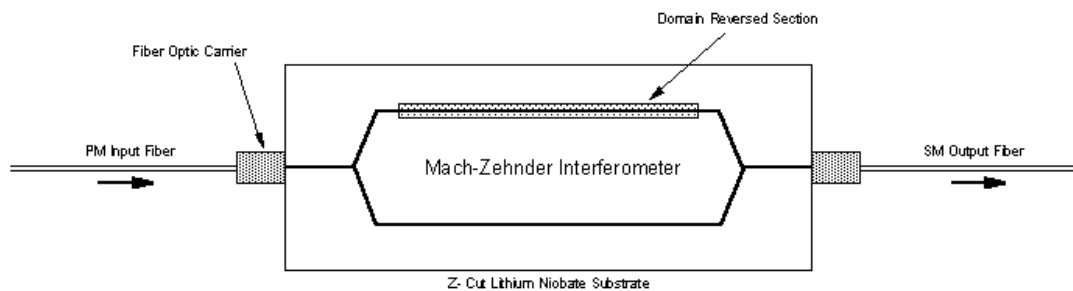


Figure 2. Schematic of the photonic electric field sensor

2.1 Device Theory

In the device structure shown in Figure 2, the Z-directed uniform electric field produces the electric field, E_z , inside the crystal. Since the electric field in the waveguides is only in the Z direction, E_x and $E_y = 0$. Only E_z is a non-zero component of the electric field vector.

This Z-directed electric field interacts with the optical beam propagating in the waveguide to produce electro-optic modulation. The electric field vector of the optical wave propagating in the waveguide is also oriented in the Z direction. This optical wave is referred to as the Transverse Magnetic (TM) mode. This electric field produced by the applied electric field modifies the refractive index of the crystal through the linear electro-optic effect. The refractive index along the Z axis (or the c axis), referred to as the extraordinary index, is n_e . The change in n_e is given by^{3,4}

$$\Delta n_e = -\frac{1}{2} n_e^3 r_{33} E_z \quad (1)$$

where n_e is the extraordinary index of refraction of lithium niobate (2.15) and r_{33} is the electro-optic coefficient of lithium niobate (30 pm/V).

Equation 1 describes the change in the refractive index in each leg of the interferometer due to electric field. The phase change in the optical beam propagating in each leg of the interferometer is

$$\Delta\phi_1 = -\frac{\pi}{\lambda} n_e^3 r_{33} E_z L. \quad (2)$$

where λ is the wavelength of the light propagating in the waveguide and L is the length of the reverse-poled region.

The device configuration shown in Figure 2 operates in a push-pull fashion. Because of the arrangement of the reverse poled region, the second leg of the interferometer sees the opposite polarity of electric field. Thus, the phase change associated with the second leg of the interferometer is, therefore, opposite in sign to that of the first leg, i.e.,

$$\Delta\phi_2 = \frac{\pi}{\lambda} n_e^3 r_{33} E_z L. \quad (3)$$

The total phase change is

$$|\Delta\phi_1 - \Delta\phi_2| = |\Delta\phi_t| \quad (4)$$

$$|\Delta\phi_t| = 2 \frac{\pi}{\lambda} n_e^3 r_{33} E_z L. \quad (5)$$

The phase shift produced by the electric field in each channel is converted to amplitude or intensity modulation at the output of the interferometer. The small signal optical response of the interferometer, at quadrature bias ($\Phi = \pi/2$), is approximated by

$$P_s = \frac{P_i}{2} [1 - \Delta\phi_t(E)] \quad (6)$$

where P_i is the input power (assuming a lossless interferometer).

The above equation shows that the output optical power is linearly proportional to the net phase shift which is a linear function of the electric field. Since this is a linear device, the detected optical signal is at the same frequency as the

voltage signal. Thus, the optical signal, P_s , would yield the necessary information regarding the electric field being measured.

3. SYSTEM CONSIDERATIONS

The following theory shows how the dynamic range of the electric field sensing system can be measured. The signal-to-noise ratio of the output from the optical receiver is mainly dependent on the amount of optical power at the photodetectors and the intensity modulation depth produced by the electric field applied to the sensor. To determine this theoretical value, the carrier-to-noise ratio is first determined. A technique for increasing the dynamic range by about 20 dB by suppressing the optical carrier is also shown.

3.1 Carrier-to-noise ratio

In a direct detection optical system the Carrier-To-Noise Ratio is given by⁵:

$$CNR = \frac{\left(\frac{\eta \cdot e \cdot P_c}{h \cdot f_c} \right)^2 \cdot R_L}{\left[\frac{2 \cdot \eta \cdot e^2 \cdot P_c \cdot R_L}{h \cdot f_c} + 4 \cdot k \cdot T \cdot F_s \right] \cdot B_n} \quad (7)$$

where η = quantum efficiency (0.6),
 e = electronic charge (1.6×10^{-19} C),
 P_c = mean optical power at the photodetector (2mW),
 h = Plank's constant (6.63×10^{-34} J.s),
 f_c = frequency (2.31×10^{14} Hz),
 R_L = load resistance (50 Ω),
 k = Boltzmann's constant (1.38×10^{-23} J/K),
 T = temperature (300 K),
 F_s = effective Noise Figure of receiving system (6 dB),
 B_n = effective noise bandwidth (20 GHz).

The numerator corresponds to the signal power developed in the photodetector load resistance. The denominator corresponds to the noise. The first term in the denominator is the quantum noise produced by the statistical arrival of photons. For the above parameters at a wavelength of 1.3 microns, this noise power component has a value of -64.0 dBm in the 20 GHz bandwidth. It is assumed that the laser source has virtually no excess intensity noise. This is reasonably true for solid-state sources like the Lightwave Electronics Model 125 laser diode pumped Nd:YAG laser, which has a high frequency shot noise floor within 2 dB of the theoretical quantum noise.

The second term in the denominator is associated with the thermal noise of the receiving system. It has a value of -58.8 dBm. Because the thermal noise is 5.2 dB higher than the quantum noise, this receiver is said to be "kT noise limited". For the values associated with Equ (1), the signal power in a receiver system presenting an effective load of 50 Ω is 78 μ W or -11.1 dBm. Based on the above calculated values of quantum and kT noise, -64 dBm and -58.8 dBm, respectively, the total noise floor is -57.6 dB. Thus, the CNR, which is the difference between the signal power and noise floor, is 46.5dB.

The receiver is said to be "quantum noise limited" if the quantum noise is equal or greater than the kT noise. The ideal situation for maximum sensitivity and dynamic range is when the quantum noise is at least 10 dB greater than kT noise. For a substantially quantum noise-limited detection, Equ. (1) reduces to the well-known expression:

$$CNR = \frac{\eta.P_c}{2.h.f_c.B_n}. \quad (8)$$

The corresponding CNR for this situation is 52.9 dB. Thus, because 2 mW of optical carrier power is insufficient for quantum noise limited detection in this receiver, the CNR is degraded by 6.4 dB.

3.2 Signal-to-noise ratio

Having established the CNR, it now needs to be seen how the Signal-To-Noise Ratio (SNR) relates to CNR. If a sinusoidal modulating tone is applied to the sensor, its optical output intensity is modulated according to the following relationship:

$$P_m = [1 + m.\sin(2.\pi.f_m.t)]P_c \quad (9)$$

where P_m = modulated carrier power or intensity,
 m = modulation index ($\ll 1$),
 f_m = modulation frequency,
 t = time.

For the analog intensity modulation of a high frequency signal, $m \ll 1$ for linearity considerations. For such a device the peak phase modulation in the interferometer is $\Delta\Phi \ll 1$.

The Signal-To-Noise Ratio (SNR) to the CNR by:

$$SNR = \frac{m^2}{2}.CNR. \quad (10)$$

If we assume that m or $\Delta\Phi = 0.1$, then $SNR = CNR - 23$ dB. Earlier we calculated that $CNR = 46.5$ dB. Thus, the corresponding $SNR = 23.5$ dB. We can thus see why it is so difficult to obtain high dynamic ranges in wideband fiber optic systems. One thing we would normally do to increase the CNR for a given received optical power would be to insure that the receiver was quantum noise limited. This we would do with a transimpedance amplifier to increase the effective photodetector load and hence lower the threshold for the quantum noise limit. Unfortunately, this option is not available at frequencies above a few GHz, due to the unavailability of suitable microwave transimpedance amplifiers. Even if such transimpedance amplifiers were available, the increase in CNR and SNR would only be 6.4 dB. We are left with only one option, and this is to increase the received optical power. However, photodetector saturation with state-of-the-art optical receivers is about 10 mW that limits use of high power laser sources.

3.3 Optical carrier suppression

One solution to this problem is to suppress the optical carrier by attenuating the power in the carrier component that provides no useful information.^{6,7} This concept is illustrated in Figure 3, in both the frequency and time domains, for the response to an optical carrier with one set of sidebands, offset by $\pm f_m$. If $FSR = 2f_m$ and the optical filter tuned to place a notch at the carrier frequency f_c then the intensity of the carrier component can be reduced by about 20 dB, without substantially affecting the sidebands. The tuning of the filter can be achieved by electrically heating the filter substrate.

The commercial optical filter product offered by Photonic Integration Research, Inc. (acquired by JDS Uniphase) has a temperature tuning coefficient of $0.01 \text{ nm}/^\circ\text{C}$ ($2.7 \text{ GHz}/^\circ\text{C}$). Alternatively, the optical carrier frequency can be tuned. The latter is easily done with a Lightwave Electronics Nd:YAG laser, which can be tuned over about 18 GHz before longitudinal mode hopping occurs and then over hundreds of GHz across many modes. Thus, there is no problem in centering the filter precisely on the optical carrier component. It can be maintained at the correct operating frequency using closed-loop control of the substrate heater or cooler or of the laser frequency.

Since the modulation sidebands are 26 dB down on the carrier component for $m = \Delta\Phi = 0.1$, we could attenuate the carrier by 20 dB and still be able to linearly detect the modulation. What we would do, in fact, would be to attenuate the carrier by 20 dB and increase the laser power by the same amount. So that, if 2 mW of optical power normally reached the photodetector, the laser power could be increased to 200 mW and after modulation it could be attenuated by 20 dB. This would cause the power detected to be still only 2 mW – the saturation power of the photodetector. It has been assumed for convenience that before the filtering process, most of the energy is contained in the carrier component. After the carrier has been partially suppressed and the power increased, the mean power in the signal remains essentially the same. Now the power in the sidebands would be increased by 20 dB, causing a 20 dB increase in the detected signal power and SNR.

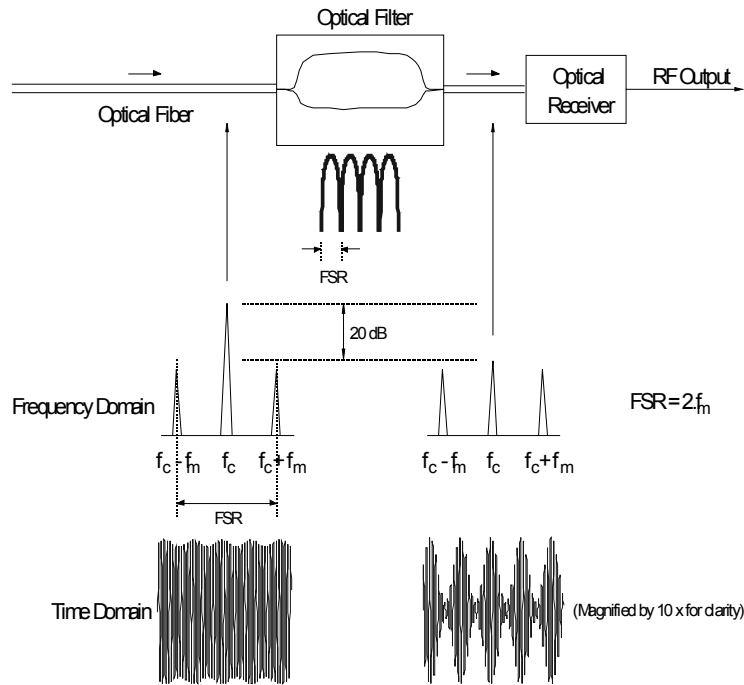


Figure 3. Carrier suppression technique to increase the dynamic range

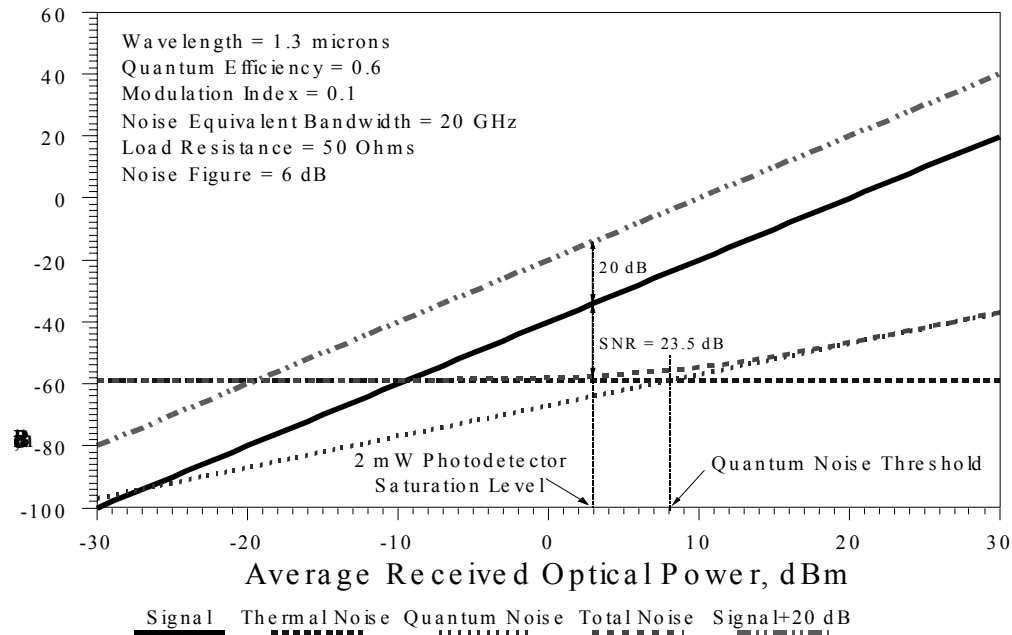


Figure 4. Graph showing signal and noise levels as a function of received optical power

Figure 4 summarizes the foregoing and illustrates graphically how the dynamic range can be improved by about 20 dB – nearly doubling (in dBm) the available dynamic range, from 23.5 dB to 43.5 dB. As previously noted, a typical photodetector saturation level for cw signals is about +3 dBm (2mW), whereas the quantum (shot) noise threshold is at +8 dBm (6.4 mW). As baseband bandwidths increase above 20 GHz, the advantage of the extra 20 dB of dynamic range becomes even more apparent. Indeed, without this extra dynamic range, such optical systems would not be viable for links that required very large instantaneous bandwidths.

Normally, the optical carrier filter would be placed just before the photodetector, as is illustrated in Figure 3. However, in some long links using very coherent laser sources (such as the Lightwave Electronics laser used in the CATV industry), there would be an advantage in placing the filter immediately after the intensity modulator, before the light is launched into the fiber. For this would help mitigate non-linear effects that degrade system performance that can occur in long single-mode optical fibers, i.e., Brillouin and Raman Scattering.

4. TEST RESULTS

The electric field sensor was tested over a wide frequency range. The low frequency test was conducted by placing the sensor inside a TEM cell and the high frequency test was conducted by placing the sensor in side a metallic waveguide. Test results are presented that show increase in dynamic range by using an optical filter.

4.1 Low frequency test, 10 MHz to 1 GHz

The fiber pigtailed electric field sensor is placed within a Crawford TEM Cell, IFI Model CC110 and tested over the frequency range of 10 MHz to 1 GHz.. The optical fibers are fed through the sloping walls of the TEM cell and connected to the laser and the photodetector via FC/APC fiber optic connectors.

The optical source is a low-noise Nd:YAG laser, Model 125 manufactured by Lightwave Electronics, Inc., operating at 1.3 micron wavelength. The optical receiver, Model 1611, is manufactured by New Focus, Inc. The output of the optical receiver is amplified by about 20 dB using a low-noise amplifier.

The RF input to the TEM cell is supplied by the Tracking-Generator available in the HP8591E Spectrum Analyzer. The output of the Tracking-Generator is amplified to a level of +30 dBm (1 Watt) and then applied to the TEM cell. The dimensions of the TEM cell are such that 1 Watt of RF power produces a peak electric field of 168 Volts/meter. The RF power travels through the TEM cell in the same direction as the propagation of light in the optical fibers and the electric field sensor.

The sensor exhibited a flat frequency response over the entire test frequency range of 10 MHz to 1 GHz. The noise floor and signal measured are -129 dBm/Hz and -57.5 dBm, respectively. Therefore, the internal electric field of 168 Volts/meter produces an SNR of 72 dB. The minimum detectable electric field is

$$E_{\min} = 168 \times 10^{-\frac{72}{20}} = 42 \left(mV / m / \sqrt{Hz} \right). \quad (11)$$

4.2 High frequency test, 7 GHz to 10 GHz

The electric field sensor was tested in the 7 to 10 GHz frequency band by placing it in a WR112 metallic waveguide fabricated by MITEC Electronics Ltd. The optical source is a low-noise Nd:YAG laser, Model 125 manufactured by Lightwave Electronics, Inc., operating at 1.3 micron wavelength. The optical receiver, Model 1411, is manufactured by New Focus, Inc. The output of the optical receiver is amplified by about 60 dB using a low-noise amplifier.

The RF field used to modulate the sensor was produced using an RF oscillator and RF waveguide system. A computer running LabVIEW for Windows controlled the amount of current into the YIG (Yttrium Iron Garnet) oscillator. The YIG converts the current into an RF signal that is carried to the metallic waveguide.

The waveguide WR112 covers the frequency range of 7 to 10 GHz. The waveguide consists of an input section to launch the RF power, a straight sections in which the sensor is place, and a conical load section to absorb the RF energy. A fiber optical feedthrough is incorporated at the input and load sections to allow entry of the fiber cables into and out of the waveguide. The maximum electric field inside the waveguide is given by⁸

$$E_{\max} = \sqrt{\frac{P480\pi}{ab} \times \frac{1}{\sqrt{1 - \left(\frac{c}{f2a}\right)^2}}} \quad (12)$$

where, P = input power to the waveguide,
a, b = width and height, 28.5 mm and 12.6 mm, respectively,
c = velocity of light,
f = microwave frequency.

The RF input power to the waveguide of 7.37 dBm (5.5 mW) is supplied from a YIG oscillator. The electric field sensor was tested at a frequency of 8 GHz. Using the above equation, the peak electric field inside the waveguide is calculated to be 175 Volts/meter.

The noise floor and signal measured at 8 GHz are -107 dBm/Hz and -31 dBm, respectively. Therefore, the internal electric field of 175 Volts/meter produces and SNR of 76 dB. The minimum detectable electric field is

$$E_{\min} = 175 \times 10^{-\frac{76}{20}} = 28 (mV / m / \sqrt{Hz}). \quad (13)$$

4.3 Use of optical filter to increase dynamic range

The optical carrier is suppressed by passing the modulated output from the electric field sensor through an optical filter. The electric field sensor was placed in a WR75 metallic waveguide that was energized by a YIG oscillator. The optical source and the receiver are the same as those used in the high frequency test of the previous section.

The optical filter was electrically tuned to null the carrier frequency resulting in a null in the output optical power. The amount of optical power that could be brought to the photodetector in this demonstration when the optical carrier was centered on a null, was about 3 μ W.

Figure 5 illustrates improvement in the SNR by suppressing the optical carrier. The top and bottom traces show the modulated signal with and without the optical filter, respectively. The electric field sensor in the waveguide was modulated at 12.5 GHz and the modulated signal was observed and measured using the spectrum analyzer. The signal-to-noise ratio (SNR) with the filter in the system was measured to be 30.7 dB with respect to a 100 kHz bandwidth, and 9.2 dB without the filter. Thus, the improvement in signal-to-noise ratio was 21.5 dB. The highest performance would be obtained by combining the carrier suppression technique with an optical detector that has a high power handling capability.

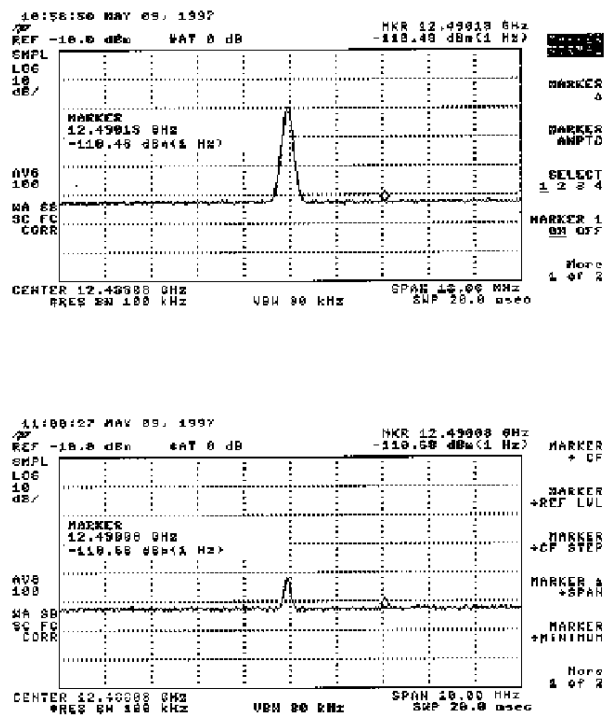


Figure 5. SNR improvement using an optical filter to suppress the carrier. Top trace with optical filter: SNR= 30.7 dB re 100 kHz. Bottom trace without optical filter: SNR= 9.2 dB re 100 kHz.

6. CONCLUSIONS

Some of the benefits of the all-optical electric field sensor over electrical devices used in the measurement of electric field are:

- The sensor provides improved measurement accuracy by reducing susceptibility to electrical noise because the sensor is made of dielectric materials
- The sensor provides non-contact measurement of electric field
- The sensor may be placed in hostile or remote areas because optical fibers are capable of transmitting signals with high fidelity in noisy environments and over long distances
- The sensor is electrically isolated providing operator and instrument safety
- The sensor is small enough to be used where space is a constraint

The electric field sensing system is capable of measuring signals over a wide bandwidth greater than 50 GHz. The minimum detectable sensitivity was measured to be 28mV in a 1 Hz bandwidth. A dynamic range greater than 40 dB in a 1 GHz bandwidth was obtained using the technique of carrier suppression.

ACKNOWLEDGEMENTS

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