An Electro-Optic Probe for Ship EMC Applications

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Abstract — This paper describes a photonic-based electromagnetic (EM) field measurement system developed for shipboard use. The system is operable from 2 MHz to beyond 18 GHz. The small probe size and all-dielectric fiber-optic cabling of the electro-optic (EO) probe allows for non-intrusive ultrawideband shipboard EMC measurements to be performed. These EMC measurements are useful for a number of Navy electromagnetic compatibility (EMC) applications requiring frequency, amplitude, and phase information. These applications include determining and verifying shipboard emission control status for tactical security, monitoring radiation hazards to personnel, ordnance, and fuel at key locations aboard ship, providing inputs for a real-time electromagnetic interference (EMI) management system, and monitoring the signal quality of individual shipboard emitters.

I. BACKGROUND

Broadband electromagnetic field sensing using EO and fiber-optic techniques has been of interest to the Navy since the first fiber-optic link demonstration in the late 1960s. Continual advances in photonic technology over the years has now made this application practical. Previous work in this area has considered antenna-coupled lithium niobate bulk crystal and integrated optical modulators (IOMs), where high sensitivities have been attained for system bandwidths below 1 GHz [1–3]. Recent work in this area includes integrated optical versions of the EM field sensing probe [4]. The class of field sensor that uses an IOM for the RF electrical-to-optical conversion is referred to here as an externally modulated field monitoring system. An alternative EO field sensing approach has focused on the direct-current modulation of an antenna-coupled, high-speed-injection laser diode [5, 6]. This approach is referred to here as a directly modulated field monitoring system. Both approaches use analog fiber-optic links to transmit the electromagnetic environment (EME) information to a remote processing site. Directly modulated, short-haul, fiber-optic systems possess a simpler design and are easier to implement, whereas externally modulated systems have been shown to be more sensitive and possess larger 3-dB bandwidths [7, 8]. This paper emphasizes the externally modulated EO EME monitoring system because of its superior performance and its better suitability of meeting ultrawideband shipboard EMC requirements.

II. SYSTEM DESCRIPTION

A schematic diagram of an antenna-coupled externally modulated EO EME monitoring system in its simplest form is shown in figure 1. Its primary components include a high-power, low-noise, polarized laser source, polarization-maintaining single-mode optical fiber (PMF) for the uplink, a calibrated wideband antenna electrically coupled to an IOM, standard single-mode fiber (SMF) for the downlink, a high-speed photodiode, and a signal processor. The signal processor consists of a wideband spectrum analyzer interfaced to a desktop computer. The compact antenna and IOM are positioned at a selected point about the ship for EM field detection, while amplitude and frequency information is remotely received and processed. The design goal of this configuration is to minimize the perturbation of the EM field by eliminating any electrical transmission lines between the probe and receiving station. Electrical power for biasing of the IOM is achieved optically via a high-power laser diode, a multimode optical fiber, and an efficient photovoltaic cell for optical-to-electrical power conversion [9]. In the present system configuration, there is no electrical amplification between the antenna and the IOM. This drastically reduces the electrical power requirements of the sensor head with the tradeoff of a higher system noise figure than the case using a low-noise amplifier. For the shipboard applications addressed here, the higher system noise figure can be tolerated.

Figure 1. Schematic diagram of an antenna-coupled externally modulated EO EME monitoring system.

Initial prototypes of the EO EME monitoring system operate from 500 MHz to 18 GHz and use a wideband spiral antenna that possesses a 50-ohm output impedance and a minimum gain of 0 dBi across this band. This system is usable at reduced antenna gain down to 2 MHz. A two-arm circularly polarized conical spiral with an 8-inch diameter is used. A schematic of this prototype system is shown in figure 2. A four-fiber, all-dielectric optical cable has been designed and fabricated for this prototype system; it allows for analog EME information as well as IOM biasing signals to be transferred to a remote site. The optics of the sensor head are packaged in a plastic box that mates to the wideband antenna via an SMA connector. Photographs of the EME monitoring system are shown in figure 3.

Figure 2. Schematic of photonic EME monitoring system with optical powering system and modulator bias control hardware.
Zehnder (MZ) waveguide modulator fabricated with traveling-wave electrodes is the modulator used in the prototype EO EME monitoring system. The expression for the output optical power as a function of the input optical power for the MZ modulator is given by

\[ P_{out}(V) = P_{in} \cos^2\left(\frac{\pi V}{2V_c}\right) \]  

where \( P_{in} \) is the input optical power, \( V_m \) is the modulator transmission loss factor, and \( V_c \) is the modulator half-wave voltage. For analog applications, in addition to the applied RF signal, a DC bias of \( V_{bias} \) is required to achieve maximum RF sensitivity. The modulator bias point must be precisely maintained over wide environmental conditions in order to keep intermodulation distortion to a minimum. A closed-loop control system to maintain the proper modulator bias position has been developed and is described in Section III. For digital applications, a modulator’s usefulness is determined primarily by its bandwidth, switching voltage, and optical insertion loss. For analog link applications, the modulator’s bandwidth, linearity, RF efficiency, and optical insertion loss are important. These parameters all play an important role in achieving high-link performance and hence, good EM field detection characteristics.

The lithium niobate MZ modulator used in the EO EME monitoring system possesses an 18-GHz modulation bandwidth, a \( V_m \) of approximately 10 volts, and a \( V_c \) of approximately 0.5. For most EMC shipboard application requirements, this performance is adequate. For future systems, higher bandwidth modulators are being developed. Lithium niobate MZ modulators with bandwidths exceeding 40 GHz are currently being developed to satisfy future shipboard EME monitoring requirements [11]. Other IOM candidates being explored for this application include III-V semiconductor-based interferometric [12] and electroabsorption modulators [13, 14] as well as polymer-based MZ modulators [15]. These modulators show the potential for ultrawideband operation but at present are still in the research and development phase.

III. SYSTEM PERFORMANCE

The technology developed in this effort has been laboratory-, field-, and shipboard-tested. The purpose of these measurements is to qualify the technology under development and provide ship operators with an example of the enhanced capabilities it can bring. The performance of this EM field-probe in the 2-MHz to 18-GHz frequency range is presented in this section.

Link Performance

The 2-MHz to 18-GHz fiber-optic link has been laboratory and field tested. During the course of this work, two different 1.32 \( \mu \)m Nd:YAG lasers, the first with an output power of 10 mW and the second with a fiber pigtail output power of 45 mW, have separately been used in the photonic sensor prototype. Both lasers have a measured relative intensity noise (RIN) value in the \(-170 \) dBc/Hz range making them extremely low noise sources. As expected, superior field detection system performance has been attained with the higher optical output power source. The lithium niobate MZ modulator has an optical insertion loss of 3.6 dB and a low frequency \( V_m = 13.5 \) V. An InGaAs p-i-n photodiode with a fiber-coupled responsivity of \( r = 0.7 \) A/W at an optical wavelength of 1.3 \( \mu \)m has been used. A trace of the overall fiber-link frequency response is shown in figure 4, which shows a 10-dBm fall off in response from 50 MHz to 18 GHz (3-dB bandwidth of 10 GHz). An optical loss from laser to detector of 10 dB has been measured, a value that includes the 3 dB for modulator biasing. For both laser powers, the received optical power for this system renders shot-noise-limited operation. The RF insertion loss of this link with the high power
laser is measured to be 32 dB at 2 GHz. The link noise figure was measured to be 40 dB, 43 dB, and 50 dB at frequencies of 2, 10, and 18 GHz, respectively. Two-tone measurements with the 18-GHz fiber-optic link show an SFDR of 108 dB/Hz. The SFDR is smaller than the linear biasing point. The optical powering and controlling of this fiber-optic link is now discussed.

**Optical Powering of Remote Fiber-Optic Link**

Many fiber-optic antenna remote applications, including shipboard EME monitoring, require standoff electrical powering of the antenna-coupled components. Self-contained battery packs are one solution. However, batteries possess a finite lifetime that can limit their usefulness for many applications. In some cases, the optical powering can be accomplished using a power-by-light (PBL) system, which has the advantage that all-dielectric fiber-optic cables can be used. This can be essential for applications like the EME monitoring system, where electromagnetic interference (EMI) effects are to be minimized. In addition, for multiple externally modulated fiber-optic links, the electrical biasing of the optical modulator is critical in minimizing nonlinear distortion. Although accurate methods of passively biasing the modulators are being investigated [16], the environmental stability of the bias position has not been established. Consequently, active modulator biasing techniques have been developed. Combining remote optical powering and remote optical modulator bias control has been demonstrated [9,17].

The PBL system consists of a high-power AlGaAs laser diode, a large core diameter multimode optical fiber, and a high-efficiency GaAs photodiode. The AlGaAs laser diode is intensity-modulated at low frequency (approximately 100 Hz) to introduce a reference modulation onto the optical modulator. The second harmonic of this low-frequency modulation is then remotely detected and analyzed using a lock-in amplifier. The output of the lock-in amplifier is used to actively control the optical power of the AlGaAs laser diode, which in turn controls the optical modulator bias voltage. A schematic of this fiber-optic system was shown previously in figure 2. A maximum of approximately 50 mW of optical power can be delivered through the optical link to the photocell which allows for an output voltage in the range between 0 and 12 V. This optical power transmission technique allows for the modulator voltage to be changed simply by varying the transmitted optical power. The adjustable transmitted optical power carries the small modulator bias depth low-frequency signal for the modulator bias control. Very little current is required (< 1 mA) to drive the modulator, from which it can be inferred that very little electrical power (voltage X current) is required for this remote unit. This is not the case if a low-noise preamplifier is included between the antenna and the modulator.

The requirement for the fiber-optic link is that the SFDR is not reduced by any error in biasing the modulator. Analytical expressions for the receiver signal powers for the fundamental through the third-order intermodulation terms can be obtained for the M2 link. For links that have bandwidths less than 1 octave, the SFDR is measured using the third-order intermodulation signals. However, if the link is designed for multi-octave bandwidth operation, as is the case here, the second-order intermodulation signals must be inspected. The spurious signal levels are dependent on the IOM bias position. The maximum allowable bias error is then calculated based on the requirement that the SFDR not be degraded by the modulator biasing. In this calculation, the receiver bandwidth is an important parameter. As the receiver bandwidth is reduced, the system noise floor is reduced, and the spurious signals become more prevalent. Therefore, the output absolute noise floor level affects the measurable spurious signal levels allowed, which determines the required modulator bias point accuracy.

The 18-GHz fiber-optic link described above has an RF insertion loss of 32 dB, a noise figure of 40 dB, and a 108dB/Hz SFDR for optimum modulator biasing. Using a 30-kHz receiver bandwidth, which is appropriate for channelized receiver or ultrawideband applications, a 1-degree IOM phase bias error for this fiber-optic link already results in its SFDR being severely limited by the harmonic levels. This implies that achieving a high phase bias accuracy is extremely difficult to attain using passive modulator biasing techniques.

A plot of the measured modulator phase bias drift versus temperature for the IOM used in the photonic sensor is shown in figure 5. An unacceptable bias point drift over the 20°C to 75°C temperature range is measured. Hence, active control of the modulator bias point is absolutely required.

The SFDR degradation due to the computer-controlled bias point stabilization for this link between 20°C and 75°C is shown in figure 6. A second harmonic suppression greater than 60 dB has been obtained that translates into increased SFDR. Using the computer control, the modulator bias point has been maintained to within 1 degree, which was limited by the time constant of the feedback circuitry. This active control technique allows the EO EME monitoring system to operate over the wide temperature ranges expected in the shipboard environment.

![Figure 5. Modulator phase bias drift as a function of temperature for the lithium niobate optical modulator.](image)

![Figure 6. Computer-controlled modulator phase bias stabilization as a function of temperature for the fiber-optic link.](image)

**Wideband RF Probe Performance**

The EM field sensing element is a crucial component of the shipboard EME monitoring system. Efficient wideband probes that can be packaged into small portable units are desired. For frequencies above 500 MHz, commercially available spiral antennas are the best choice. Compact spiral antennas are available with responses from 0.5 to 50 GHz. The gain as a function of frequency of a 0.5- to 18-GHz, two-arm, circularly polarized, omnidirectional spiral antenna is shown in figure 7. A gain of greater than 0 dB is obtained for frequencies greater than 500 MHz. Below 500 MHz, the response of this antenna drops off dramatically. It appears to behave similarly to an electrically short dipole antenna. At 300 MHz, a gain of approximately -70 dB is measured, and at 10 MHz, a gain of approximately -70 dB is measured. This is one of the spiral antennas used in the prototype photonic EM field sensor. For the fiber-optic link described above, along with a receiver bandwidth of 30 kHz, minimum detectable electric field strength using this antenna of 0.3 V/m, 0.005 V/m, and 0.6 V/m at 10 MHz, 500 MHz, and 18 GHz are predicted. Results of actual EM field measurements are now presented.
Electromagnetic Field Measurements

Initial testing of the EO EME monitoring system was carried out using the low power Nd:YAG laser. Remote electromagnetic field measurements in the 2-GHz to 18-GHz frequency range were made. The wideband RF probe used for these initial measurements was a 2-inch-diameter, cavity-backed spiral antenna instead of the 8-inch spiral discussed above. It is a left-hand circularly polarized antenna that has a 3-dB beamwidth of 80 degrees and a voltage standing wave ratio (VSWR) of less than 2:1 across the 2- to 18-GHz frequency range. The gain versus frequency characteristics were measured against standard gain horn antennas in the 2- to 18-GHz range for linearly polarized radiation, and greater than 0-dBi gain exists for frequencies above 4 GHz.

EM field measurements were made with the antenna-coupled fiber-optic link after separate testing of the antenna and link was completed. A 2- to 18-GHz far-field anechoic chamber was used in which to perform the experiments. Measurements were performed at 2.25, 9.52, and 16 GHz using three different standard gain horn source antennas. The EM field detection system response for boresight radiation at the three frequencies investigated is shown in figure 8. A 10-Hz spectrum analyzer resolution bandwidth was used in this measurement. Extremely linear response is obtained from the highest field levels down to the minimum detectable levels for each frequency investigated. To assess the accuracy of these field measurements, electric field values were obtained from the detected optical power levels, since the RF insertion loss of the link as well as the gain of the antenna were known. The result of this measurement is shown in figure 9 where measured field strengths are plotted versus calculated electric field strengths. There is some deviation from expected field levels, which is attributed to the anechoic chamber testing procedure. The pointing accuracy for the three relatively high-gain horn antennas was not precisely controlled, resulting in actual electric field levels that differed from the calculated levels. Nonetheless, RMS electric field sensitivities of approximately 15 µV/m, 44 µV/m, and 107 µV/m have been achieved in a 1-Hz resolution bandwidth for the 2.25-, 9.52-, and 16-GHz frequencies, respectively. These results were obtained using the low-power laser source and the slightly less efficient 2-inch spiral antenna. Superior performance from 2 MHz to 18 GHz has been achieved with the present monitoring system employing the high-power laser and the 8-inch spiral antenna. The RMS electric field detection ranges for the present EO EME monitoring system at 10 MHz, 2 GHz, and 18 GHz are summarized in table 1. These experimentally attained electric field detection ranges imply that this system can be useful for remotely performing broadband, large-dynamic-range electric field measurements.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>1-Hz Bandwidth</th>
<th>1-kHz Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>50 µV/m – 5 V/m</td>
<td>0.05 V/m – 500 V/m</td>
</tr>
<tr>
<td>2.0</td>
<td>1 µV/m – 0.1 V/m</td>
<td>0.001 V/m – 10 V/m</td>
</tr>
<tr>
<td>18.0</td>
<td>30 µV/m – 3 V/m</td>
<td>0.03 V/m – 300 V/m</td>
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Shipboard Testing

The prototype EO EME monitoring system was shipboard-tested in 1994. The prototype photonic sensor assembly is mounted at selected topside positions while controlled shipboard emissions are recorded. The LSD 47 ship has been used for in-port testing which occurred in March 1994. At-sea testing was performed aboard the CG 62 ship in November 1994.
EM configuration of this ship, it appears that vision bands are clearly detected. The test condition with the seven trans-frequency range were recorded aboard this Aegis class cruiser. This proposed monitoring site, an average field strength due to each emitter testing aboard the CG 62 Navy surface ship. However, due to the topside on the aft close-in weapon system (CIWS) platform. This probe site is on EME for the docked LSD tonic sensor with their signals fading in and out due to their highly direc-
easy detected. SHF radar transmissions were also detected with the pho-

\[ S = \frac{P_{t}}{4\pi R^2} \] 

where

- \( S \) = received power density (W/m²)
- \( P_{t} \) = emitter level (W)
- \( G \) = transmit antenna gain (dB)
- \( R \) = radius (m), antenna to sensor

For the higher frequency transmitters, this approximation gives fairly accurate results. For the high-gain antennas, conservative field strength estimates are made using sidelobe field strength levels instead of mainlobe field levels. For high-power pulse-mode operation, peak power levels are used for estimating field strengths. With this approach, first-order estimates of the average field strength at various topside locations can be made.

Previous EME measurements in the HF band for the LSD 47 have been made at 16 different sites about the ship, and those measurements have been used for estimating purposes [18]. From the available experimental HF data and the estimated EM field levels above HF, it appears that a single topside sensor site for LSD 41 class surface ships is all that is required to obtain the entire ship EM signature and determine the status of every shipboard emitter. The candidate topside measurement site is located on the aft close-in system (CIWS) platform. This probe site is on the 07 level, C/L, approximately 25 meters from the base of the mast. With this proposed monitoring site, an average field strength due to each emitter of at least 0.1 V/m should be registrable at the topside measurement location. This field strength should be detectable with the photonic EM field probe.

As an example of the on-ship data collected, the background or ambient EME for the docked LSD 47 is shown in figure 10(a) where radio and television bands are clearly detected. The test condition with the seven transmitters activated is shown in figure 10(b). All seven transmitted signals are easily detected. SHF radar transmissions were also detected with the photonic sensor with their signals fading in and out due to their highly directional and rotating characteristics. Similar data were collected during at-sea testing aboard the CG 62 Navy surface ship. However, due to the topside EM configuration of this ship, it appears that some sensor sites are required to obtain its EM signature. Emissions spanning the 2-MHz to 18-GHz frequency range were recorded aboard this Aegis class cruiser.

10(a) Background Level (Nothing Active)

![Background Level](image)

10(b) Test Condition (7 Emitters Active)

![Test Condition](image)

Figure 10. Photonic EME monitoring system output for LSD-47 with (a) no transmitters active and (b) seven transmitters active.

IV. APPLICATIONS

The shipboard EME routinely consists of high-level, on-ship emissions extending from the HF into the EHF bands. Rapid advances in the areas of radar, electronic warfare, and communications technologies are making this EME more complex and at the same time more difficult to manage. The proliferation of topside transmitting antennas has increased the need to monitor these emissions and to dynamically perform topside frequency management to minimize electromagnetic interference. To address these needs, the Navy is seeking small, affordable, broadband shipboard EME monitoring tests and systems that insignificantly perturb the desired radiated emissions.

A primary Space and Electronic Warfare (SEW) Support Function is Signals Management, which includes the subdiscipline Emission Control (EMCON) Management. EMCON management not only has application across the entire SEW battle space, it also greatly influences the effectiveness of other warfare areas such as Strike and Air Warfare. A shipboard EME monitoring system for real-time EMCON management can ensure the electromagnetic interoperability of hardkill/softkill offensive and ship self-defense systems. This is a vital capability of our future fleet.

A topside EME sensor that can provide frequency, amplitude, and modulation information of simultaneous broadband emissions is also useful to upgrade the current shipboard quality monitoring system (QMS) capability. Here, radiated signals are monitored instead of the current approach of sampling the antenna input electrical signal. Real-time monitoring of hazardous radiation levels for personnel (HERP), ordnance (HERO), and fuel (HERF) at key topside locations is a key benefit of a shipboard EME monitoring system.

For many years, the Navy has been developing technology and solutions to ship and battle force EMI problems. A topside EME sensor will be used as part of an on-board system for on-line real-time control of combat and communication system frequency assignments to control EMI in a dynamic warfare environment. This shall allow our shipboard communications, surveillance, and combat systems to operate at peak effectiveness in quickly changing threat environments. This is a vital capability that can be enabled by the shipboard EME monitoring system.

V. SUMMARY

The concept of using fiber-optic and EO techniques for shipboard remote broadband EM field monitoring has been demonstrated. The system consists of a compact spiral antenna, an optically powered and controlled ana-

log fiber-optic link, and a wideband spectrum analyzer. A single RF probe design for continuous 2-MHz to 18-GHz frequency coverage has been demonstrated. Laboratory, anechoic chamber, and shipboard measurements have been performed in the 2-MHz to 18-GHz frequency range on the prototype EO EME monitoring system. Electric field sensitivities of less than 1 V/m in a 30-kHz bandwidth with a spurious free dynamic range greater than 75 dB have been demonstrated with this system. The performance of this system is limited at the high-frequency end by the optical modulator and at the low-frequency end by the gain of the compact antenna.

In summary, it has been found that shipboard EO EME monitoring is currently feasible for frequencies up to 20 GHz using an externally modulated fiber-optic system. Systems with frequency coverage to 40 GHz should be possible in the near future as optical modulator performance is improved. A successful shipboard demonstration has been performed to validate this system.
VI. REFERENCES


