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Delivery Order 0004: Fiber-Optic RF Distribution (FORD) (PREPRINT)

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Fiber-optic cable has beneficial characteristics of extremely low cross coupling and is not conductive along its length; this equates to tremendous promise as a means for distributing RF signals with limited EM/RFI. The innovative concept is applicable to PCBs which have a level of RF signals traversing near multiple sensitive RF circuits.

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Fiber Optic RF Distribution (FORD)

Investigations in Fiber Optics as a means for distributing RF to mitigate inter-board EMI

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ABSTRACT

The use of fiber optics is considered herein as means to distribute Radio Frequency (RF) signals across Printed Circuit Boards (PCB). The use of fiber optics is studied with an emphasis on reducing inter-board Electromagnetic Interference (EMI). High performance RF circuits are especially sensitive to EMI and other Radio Frequency Interference (RFI), resulting in poor circuit-to-circuit isolation, spurious signals, additional filtering requirements, and increased shielding constraints.

Fiber optic cable has the beneficial characteristics of extremely low cross-coupling and is not conductive along its length; this equates to tremendous promise as a means for distributing RF signals with limited EMI/RFI. The innovative concept is applicable to PCBs which have high level of RF signals traversing near multiple sensitive RF circuits.

Keywords: RF Distribution, FORD, Fiber Optics, Inter-board EMI, RFI, High Performance RF, Circuit Isolation, Spurious Signals, High Speed Digital Interference, Undesired Emissions, Electromagnetic Interference

1. INTRODUCTION

The primary focus of this study is to investigate the state-of-the-art in fiber optics and employ that knowledge to establish the feasibility of using fiber optics to distribute RF signals throughout a printed circuit board (PCB). Distributing RF signals across a PCB has the potential for Electromagnetic Interference (EMI) issues, especially for sensitive RF circuits. Undesirable

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effects of EMI show up as spurious signals and poor circuit-to-circuit isolation. The special attraction to using fiber optics is due to the beneficial characteristics associated with a fiber optic cable as a communication conduit. A length of fiber optic cable is non-conductive along its length, which is expected to severely limit the amount of undesired coupling of electromagnetic energy down the path of the fiber. Also, fiber optic uses modulated light instead of electromagnetic energy at Radio Frequency (RF) as the propagation approach. The result is that the fiber optic is less susceptible to electromagnetic interference and conversely, the fiber optic will not generate EMI for the PCB circuitry. Together, these desirable characteristics are anticipated to significantly lower the potential for inter-board EMI when distributing RF signals. This study will provide data to support the idea that distributing RF signals across a PCB using fiber optic cable is a feasible approach.

This innovative concept is directly applicable to PCBs which have RF signals traveling across sensitive RF sub-circuits. In order to assess the susceptibility of fiber optic transmissions to EMI, RF signals will be passed using fiber optics and characteristics of interest will be measured.

2. STATE OF THE ART IN 2006

Spurred on by the promise of enormous bandwidth delivered at great distances and at comparatively low cost, fiber optic technology has progressed rapidly over the last decade. The advances continue through today and projections do not even hint at a "completely exploited" technology. There are continuing advances with higher bandwidth and for ever greater distances. Additionally there are innovations in low cost devices and in smaller, integrated form factors. Trends point to increasingly viable solutions for board to board interconnects.

FIBER OPTIC CABLE

Fiber optic cable has become common place and is widely used in communication systems, particularly for high volume data traffic. It is especially useful in long distance applications due to its large data carrying capacity and its extremely low attenuation loss over distance. Fiber optic cable carries many Gigabits of data per second (Gbps) and has transmission losses that are a fraction of other transmission medium such as coaxial cable, wireless transmissions, telephone lines, and wired Ethernet lines. In addition to the advantages of high data rate and low transmission losses, fiber optic cables are relatively very light weight and environmentally rugged.

Thin fibers made of glass and more recently plastic are used to construct fiber optic cables. The thin fibers are continuously drawn in the manufacturing process and so can be made to any length. Fiber optic cables can consist of a single optical fiber strand or multiple strands bundled together. To pass information using a fiber optic cable, tightly focused light is directed into one end of the optical fiber. Due to the very low angle of incidence to the fiber optic walls, the light reflects along the inside of the fiber as if it were a mirrored surface with low loss. Often a dark coating is used to cover the optic fiber in order to accentuate the boundary layer and provide a more efficient mirror effect.

Fiber optic cables are classified into two types according the mode of transmission of the light. The two types are single mode and multimode. Single mode is a single strand of glass or plastic fiber that has only one mode of transmission. This single strand typically has a diameter between 8.3 and 10 microns and propagates light with wavelengths of either 1310 nanometers (nm) or 1550 nm. These two light wavelengths have become standards due to the lower loss associated with this cable type. The single mode fiber can handle a higher transmission rate than the multimode. It has a smaller diameter and provides less signal distortion than the multimode type. Single mode fiber is generally used for long-haul digital communication applications. Long-haul communications is that which is measured in kilometers, with representative distances of hundreds of kilometers.

The multimode type of fiber optic cable is made of glass fibers with diameters from 50 microns to 100 microns, with the most common diameter at 62.5 microns. These diameters are a minimum of 5 times larger than the single mode type. The multimode is used more for medium distances. There are again two commonly established wavelengths of light for the multimode type; 850 nm and 1300 nm. The primary limitation to propagation distance for the multimode is a physical phenomenon associated with light propagation called dispersion. Dispersion results from the fact that different wavelength light travels through the fiber optical cable at slightly different speeds. As the distance increases the modulated light, which consists of light with slightly different wavelengths due to the modulation process, experiences a "smearing" effect due to dispersion. This dispersion limits the data rate per distance that multimode fiber cable can support. Multi-mode fiber is generally found in local area networks based on 10BaseT and 100BaseT applications between or even within buildings. Multi-mode fiber is less expensive than single mode fiber.

This study is addressing the specific application of using fiber optic cable to distribute RF signals between and within PCBs. Both single mode and multimode cable type is applicable since the distance run is not long enough for either transmission losses or dispersion to have a significant effect. A plastic optical fiber (POF) is even a possibility because of the short transmission distances. POF has performance similar to glass cable on very short runs and costs less than glass.

OPTICAL TRANSMITTERS

The function of the transmitter is to convert an electrical signal into an optical signal. This is done in two parts; one part that interfaces to the applicable electrical input signal (i.e. TTL, ECL, or CMOS) and the second part that is the source driver of the optical signal into the optical fiber. The two most common types of optical sources are the Light Emitting Diode (LED) and the Laser Diode (LD). There are different source drivers depending if the electrical signal represents digital data or an analog waveform. The source driver imparts modulation onto the optical signal in the form of light pulses when representing digital data and by varying the light intensity in a manner that conveys the original electrical signal when representing analog waveforms. Another method for modulating both digital and analog signals is by varying the wavelength of the transmitted light in relationship to the electrical input. For digital data this would consist of light at one of two different wavelengths. For analog electrical waveforms the wavelength of the light would be continuously variable over a range sufficient to represent the analog waveform. The comparative relationship between digital data rates, expressed in terms of bits per second (bps), and the bandwidth, given in Megahertz (MHz), required for analog waveforms is that it takes twice the data rate to equal an approximately equivalent bandwidth value. For example, a transmitter capable of a 2 Gbps data rate would have a more or less equivalent analog bandwidth of 1 GHz.

The optical transmitters are usually mounted in a plastic package which mounts closely with the fiber optic cable in order to couple as much light into the fiber as possible. Some transmitters even have spherical lenses to better focus the light into the fiber. Another method used with transmitters has the fiber precision glued to the light emitting surface of the transmitter.

Both types of optical transmitters operate at the common operating wavelengths of 850 nm, 1310 nm, and 1550 nm. The two types of optical sources (LED and LD) have different performance and their use is typically dependent on the transmission distance. LEDs have relatively large light emitting surfaces and consequently do not concentrate as much light energy into the fiber as a laser diode. This lower light intensity, plus the fact that LEDs require less support circuitry are important reasons that LEDs are more often used for short to medium length transmission distances. Another reason is that LEDs are more stable over temperature variations. The laser diode requires more elaborate support circuitry and is not as stable over temperature, however its ability to inject much more light energy into the fiber cable make it the transmitter of choice for high data rate, long distance applications. The additional circuit complexity and stability over temperature concerns are justified by the higher performance. The overall speed of the transmitter is a major limiting factor in the transmission speed of an optical system. LEDs have transmission bandwidths in the hundreds of MHz while laser diodes are approximately ten times faster. Transmitter speeds are given in either Gbps rates for digital data applications or in MHz for analog applications.

Two common laser diode types that are used for high speed transmission is the Fabry-Perot laser and the Distributed Feedback (DFB) laser. Both laser diodes efficiently convert electrical signals into highly focused light.

Fabry-Perot lasers use mirrors to direct the light back and forth across a cavity and one or both of the mirrors transmit a fraction of the resonant frequency. The cavity is such that a standing wave is formed between the mirrors. The frequency of the transmitted light is contingent upon the wavelength of the light having an integer number of wavelengths in the complete path from a mirror to the other side and back again. Figure 1 shows the construction of a Fabry-Perot laser.

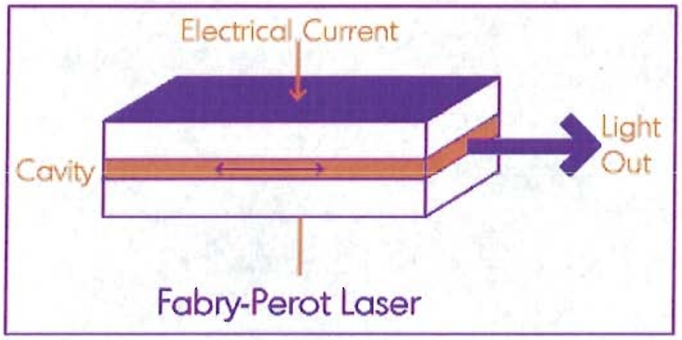


Figure 1: Fabry-Perot Construction *[2]*

The Distributed Feedback (DFB) lasers use built-in grating rather than mirrors that leads to a periodic variation of the mode index. The grating partially reflects some of the light as it passes. A diagram of the construction of a DFB laser is shown in Figure 2. The spacing between the gratings controls the phasing and hence the frequency of the transmitted light. This results in the DFB laser having a much narrower bandwidth. Since the energy is transmitted out of the side of the laser, coupling efficiencies are lower than that of the VCSEL. DFB lasers can be found in both short and long haul communications systems.

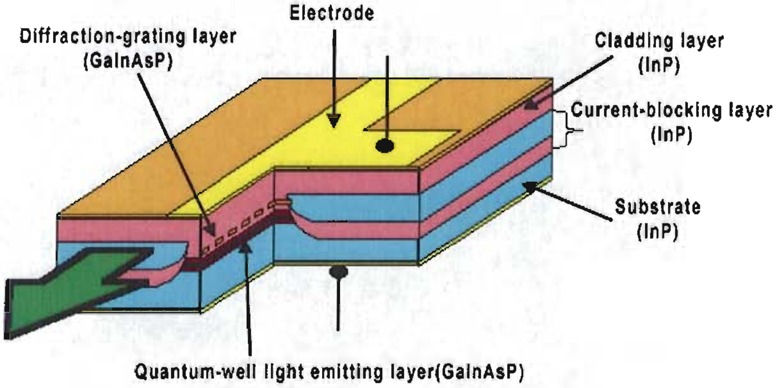


Figure 2: Distributed Feedback (DFB) Construction *[3]*

More pertinent to the focus of this study is the Vertical Cavity Surface Emitting Lasers (VCSEL) based optical transmitter. This very promising laser transmitter combines the ease of use of LEDs with the impressive speed of laser diodes. Figure 3 shows the construction of a VCSEL. The VCSEL is a semiconductor laser that operates in a single longitudinal mode via a small cavity length (~1um)*[4]*. Emitted energy is in a circular pattern from the center of the laser that couples to fiber optic cable very efficiently.

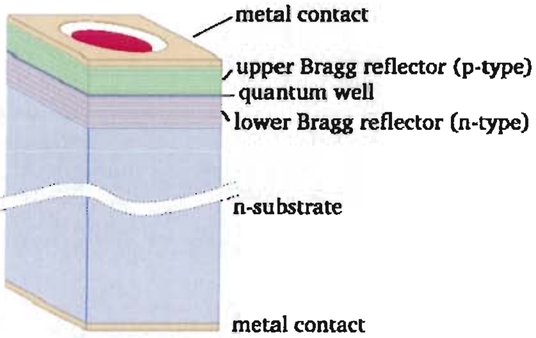


Figure 3: Vertical Cavity Surface Emitting Lasers (VSCEL) Construction *[4]*

OPTICAL RECEIVERS

The optical receiver converts the modulated light within the optical fiber back into an electrical signal. It is the direct compliment of the optical transmitter. It consists of two parts, one part to detect the light signal and the second part to interface to the electrical hardware. Similar to the transmitter, optical receivers are available in digital data and analog waveform versions. Optical receivers are usually implemented by utilizing photodiodes, either a PIN type or an Avalanche type. Like the transmitter, the receiver is mounted in a plastic package that mounts closely to the fiber optic cable. The proper alignment of the fiber optic cable to the detector area of the photodiode, to a much lesser extent than the transmitter, is important to achieving proper performance. This is due to the relatively large detector area of the receiver.

Receivers are available in the three common wavelengths of 850 nm, 1310 nm and 1550 nm. These three wavelengths were established to take advantage of lower loss in the fiber optic cable and the most sensitive receiver bands.

The application that concerns this study has the advantage that the transmission distances will be such that the received light level will always be well above the sensitivity thresholds of the photodiodes. Optical receivers have large amounts of gain in order to increase the received light to a level that can be buffered and processed. This large amount of gain should be carefully controlled. While the fiber cable is insensitive to electromagnetic interference, the receiver with its high gain is not. Proper shielding and layout are critical to producing optimal results.

FIBER OPTIC CONNECTORS

Many fiber connector standards have been established over the years. The most prevalent connectors in North America are recognized under the Telecommunications Industry Association / Electronic Industries Alliance (TIA/EIA). Some common connectors used today are described in the TIA/EIA standards FOCIS-6, FOCUS-10, and the FOCUS-12. Some common connectors from the TIA/EIA standards are the FJ, LC, and the MT-RJ fiber optic connectors shown in Table 1, Common Fiber Optic Connectors.

Selecting a connector is dependent upon the nature of the environment that the systems will be subjected to. A semi-clean environment, that is not prone to shock and vibration could tolerate the standard FC and ST type connectors. If the environment is a harsh and dirty environment that will undergo shock and vibration, a connector similar to the ITT PHD series connector would be suitable.

When choosing a connector, items to consider include: insertion loss, connector repeatability, and the type of cable you will be using. Insertion loss can sum to substantial losses if multiple connectors are used in a communication path. Repeatability measures the consistency between terminations and ease of installation. Fiber type can be either single or multi-mode. Mixing single-mode cable and multi-mode connectors or vice versa can lead to communication failures and are not recommended.

This study will use connectors of type ST and LC, due to availability and ease of use.

Connector	Insertion Loss	Repeatability	Fiber Type	Applications
FC	0.50-1.00 dB	0.20 dB	SM, MM	Datacom, Telecommunications
FDDI	0.20-0.70 dB	0.20 dB	SM, MM	Fiber Optic Network
LC	0.15 db (SM) 0.10 dB (MM)	0.2 dB	SM, MM	High Density Interconnection
MT Array	0.30-1.00 dB	0.25 dB	SM, MM	High Density Interconnection
SC	0.20-0.45 dB	0.10 dB	SM, MM	Datacom
SC Duplex	0.20-0.45 dB	0.10 dB	SM, MM	Datacom
ST	Typ. 0.40 dB (SM) Typ. 0.50 dB (MM)	Typ. 0.40 dB (SM) Typ. 0.20 dB (MM)	SM, MM	Inter-/Intra-Building, Security, Navy
MTP/MPO	< 0.35 dB	< 0.20 dB	SM, MM	High Density Interconnection
PHD (ITT Cannon)	< 0.15 dB	< 0.20 dB	SM, TSM, MM	High Density Interconnection Multiple connector packages
MT-RJ	0.30 dB	< 0.2 dB	SM, MM	High Density Interconnection
VF-45	< 0.30 dB	0.10 dB	SM	Datacom
MU	< 0.20 dB	< 0.20 dB	SM, MM	Datacom
FJ	0.2 db	< 0.20 db	SM, MM	High Density Interconnection

Table 1: Common Fiber Optic Connectors *[5]*

TECHNOLOGY TRENDS

Research conducted into the trends of implementing VCSEL fiber optic systems revealed two distinctly interesting papers. The first paper was published by EDN.com *[6]* and the second by a particle physics group located at the University of California *[7]*. Both papers touch on multiple items, but the common focal point is the implementation of VCSEL technology. The University of California presentation from November 2005 points out the following:

- VCSELs dominate where DFB laser or high power is not needed
- Many suppliers at the 1 Gbps level (the experiment uses 2.5 Gbps devices)
- Reliability established at 850 nm
- 1300 nm devices have been slow to reach commercialization
- Low cost visible VCSELs becoming available at 635 and 650 nm
- Expected bandwidth between 3 Gbps and 10 Gbps

Additionally, a noted trend is the implementation of short-haul and ultrashort-haul services into intermediate-reach applications. Ultrashort haul services are essentially inter-board communications (typically less than 12 inches), similar to the focus of this study.

This interest in the special characteristics of VCSEL technology manifests itself as many research papers on various topics associated with VCSELs, development funds for VCSEL based systems, and reference designs incorporating VCSEL diodes. The sheer magnitude of price differential from the older laser diode transmitter systems to the VCSEL systems makes the VCSEL an ideal candidate for short-haul and ultrashort analog fiber link (AFL) communications. This fact alone will likely accelerate the implementation of VCSEL technology into AFL systems.

Greatly easing the implementation of fiber optic systems throughout the communications industry is sophisticated fiber optic modeling software. A brief survey of Fiber Optic software was initiated to explore the present-day Computer Aided Design (CAD) tools available. Fiber optic modeling software was sought to assist in characterizing and quantifying fiber optic links for this project. Simulation of systems greatly enhances the potential for success and facilitates in understanding the trade-offs associated with system level performance. Two candidate software programs were identified; RSOFT and OptiWave. Both programs offer simulation systems for modeling fiber optic communication systems. OptiWave was chosen and used for modeling the implementation. The results of the modeling and simulation are included in the subsequent section.

3. CONCEPTUAL APPROACHES

INNOVATIVE IMPLEMENTATION OF COTS PRODUCTS

The research conducted for this study paper revealed several innovative implementations that utilized Commercial Off the Shelf (COTS) products. An interesting example which illustrates the high performance capability of fiber optic systems is the Large Millimeter Array network *[8]*. This network is under control of multiple radio astronomy observatories. These radio observatories have designed and implemented wide ranging fiber optic networks to synchronize signals between antenna arrays and the central processing facility. A specific illustration of this network is the Atacama Large Millimeter Array (ALMA). ALMA implements fiber optic systems for remoting local oscillators, intermediate frequencies, and other antenna remoting functions. Data rates for the remoted systems are in the neighborhood of 10 Gbps. A second astronomy system , this time with cost considerations, is the Allen Telescope Array (ATA) *[9]*. Both systems implement analog fiber links (AFL).

PRACTICAL APPROACH

A block diagram for an early conceptual approach that was proposed for this study is shown in Figure 4. This approach utilized high-speed emitter coupled logic (ECL) technology to convert RF signals into digital waveforms and represented a practical utilization of fiber optic cable. The fiber optic transmitter and fiber optic cable are readily available components. The corresponding fiber optic receiver and ECL-to-RF converter also promised to be readily available components. It was intended that RF buffer/amplifiers would isolate external circuitry from the ECL and RF converters. These are shown as the amplifiers in Figure 4.

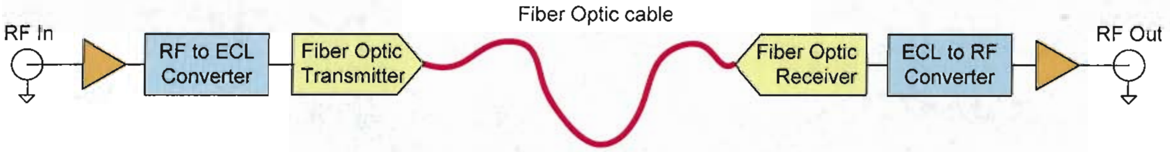


Figure 4: Conceptual Approach to Distributing RF Over Fiber

MODELING AND SIMULATION

It became apparent early on in the project that it would be beneficial to determine the feasibility of this concept through modeling and simulation. OptiWave's OptiSystem 5 modeling software was used to perform the optical system simulation. The simulation software emulated the VCSEL and PIN photodiode in a fiber optic circuit. By simulating various scenarios with the software, it was determined that an RF signal could be directly transmitted through a fiber optic system. Figure 5 shows a screen shot from the fiber optic simulation software. A very simple fiber optic link is simulated which consists of a transmitter diode, some fiber cable, and a photodiode for receiving. The diode functional blocks are easily recognized. Note the functional blocks for measurements such as RF spectrum analyzers, optical spectrum analyzers, and an Eye diagram Analyzer.

The noise resulting from the software simulation generated some concern. The simulated output resulting from an applied -10 dBm signal had a noticeably elevated noise floor. It was speculated that the noise floor was directly connected to the conversion process of the optical transmitter. The source of the simulated noise floor was not decisively identified.

The measured phase noise did not completely correlate with the simulation, which is not totally unexpected. The software model is only as good as the mathematical model it represents. There may also be additional circuit data that should be included in our software model to bring the simulation and measured to closer agreement. The precise reason for this discrepancy was not determined and warrants further examination. The measured data from an actual fiber optic link was deemed more important than the simulation results in determining the performance of an AFL.

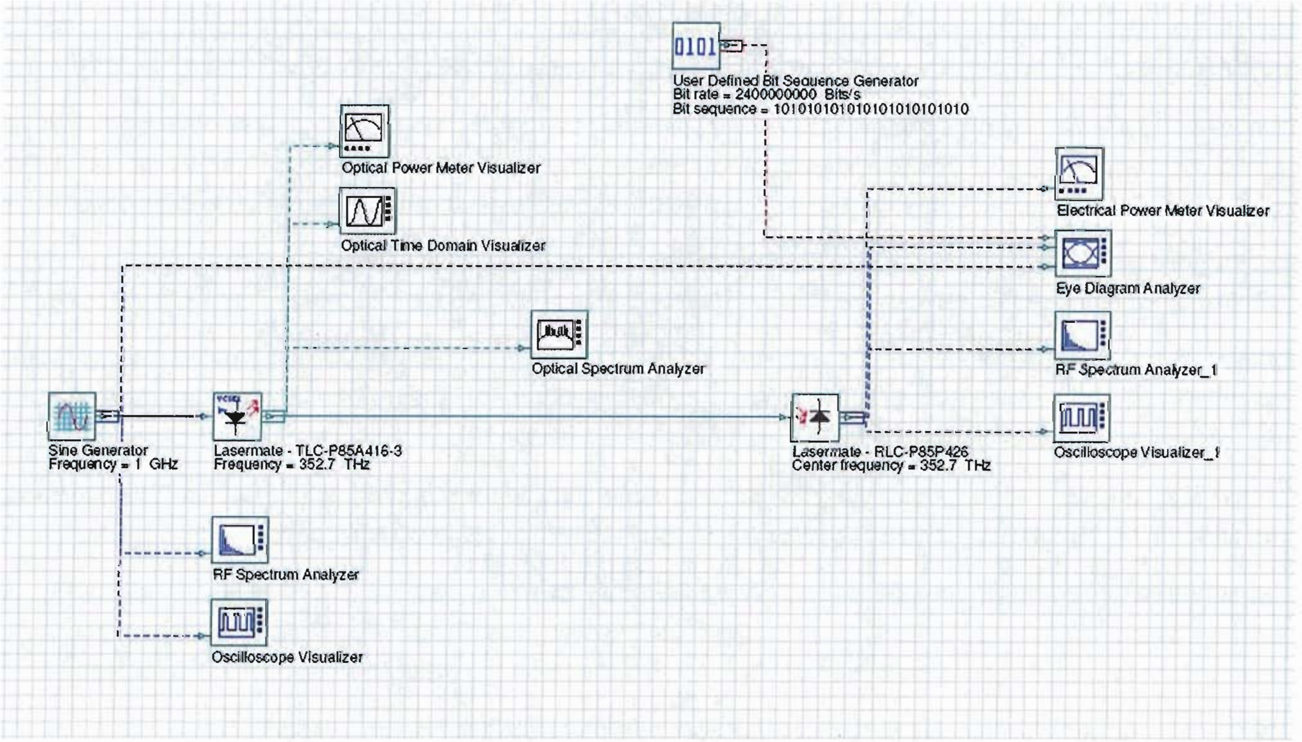


Figure 5: Simulated Block Diagram using OptiSystem 5

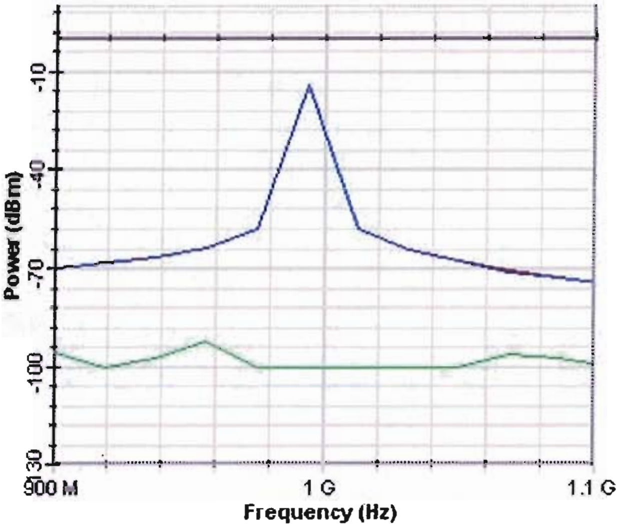


Figure 6: Simulated RF Output Using OptiSystem 5

Figure 6 represents the RF Output of the simulated circuit in Figure 5. The blue trace represents the RF output and the green trace represents the simulated noise floor of the circuit.

THE COST FACTOR

A key factor in determining the feasibility of a fiber optic system for distributing RF is the piece part price of such a system. To evaluate the cost factor, published prices were tracked and quotes were solicited for commercial pricing. This compiled data is valuable as an estimate of the cost to implement a fiber optic system for distributing RF across and between PCBs.

Several companies are offering fiber optic transceivers which can perform at the 2.5 Gbps data rate and beyond.

Company	Website	Transmitter	Technology	Price
Microwave Photonic Systems	http://www.b2bphotonics.com	MP-2300TX	Fabry-Perot	$1950
MITEQ	http://www.miteq.com	LBL3GHz	DFB	$2,100
MITEQ	http://www.miteq.com	SBT-2500	DFB	$1,150
Optocom	http://www.optocom.com	OPT3445-5.0	DFB	$399
Lasermate	http://www.lasermate.com	TLC-P85A416-3	VCSEL	$25

Table 2: Fiber Optic Transmitter Companies and Pricing

Table 2 displays a few of the companies that are offering fiber optic transmitter systems that claim to have RF performance < 2 GHz. Three of the five systems listed are direct drop-in modules. They have a standard SMA RF connector for the input and may be assembled with the fiber optic connector that is chosen for the intended environment. Four out of five components in Table 2 display data based upon either Fabry-Perot or Distributed Feedback (DFB) laser technology.

The pricing differences in DFB, Fabry-Perot, and VCSELs are based upon the manufacturability of the components. DFB and Fabry-Perot lasers cost more to build due to their complex construction methods. VCSELs are used today for short distance, high-speed communications. Distances can range from less than a meter to several hundred meters. Usually, VCSELs will be used as interconnects for a local area network between an array of office buildings. Pricing was obtained for the Lasermate VCSELs and is shown in Table 2. In small quantities, VCSEL lasers will cost approximately $25 while quantities greater than 100 will see a decrease in cost to about $10 per laser.

Likewise, the same companies that offer transmitters are also building receivers for their systems. These are presented in Table 3. The transmitters and receivers are not sold as pairs, but as separate items. As with the Lasermate transmitter, the receiver will also be sold at about $10 for quantities greater than 100. The higher priced receivers are rated at a maximum throughput of 2.5 – 3.0 Gbps. The low-end Lasermate PIN Photodiode has a maximum data rate of 2.5 Gbps.

Company	Website	Receiver	Technology	Price
Microwave Photonic Systems	http://www.b2bphotonics.com	MP-2320RX	PIN Photo	$1350
MITEQ	http://www.miteq.com	LBL 3GHz	PIN Photo	$1,500
MITEQ	http://www.miteq.com	SBT-2500	PIN Photo	$1,100
Optocom	http://www.optocom.com	OPT1455-5.0	PIN Photo	$193
Lasermate	http://www.lasermate.com	RLC-P85P425	PIN Photo	$25

Table 3: Fiber Optic Receivers

The receiver systems typically will include a photo-detector and associated circuitry that will assist in recovering the RF signal. Three of the five systems listed are direct drop-in modules for an RF-over-Fiber distribution system.

Sample pricing from two companies, Cable Wholesale and Black Box, which both sell terminated and un-terminated fiber optic cable is listed in Table 4. Un-terminated, single-mode cable will need to be terminated with single-mode connectors. ST type single-mode connectors sell for $16.95 each from Black Box.

Cable Wholesale	Price	Black Box	Price
Terminated Single-Mode		Spooled Single-Mode	
1 meter	$34.65	500 feet - 6 fiber cable w/ PVC jacket	$299.95
2 meter	$35.70	500 feet - 6 fiber cable w/ Plenum jacket	$333.95
10 meter	$44.10	500 feet - 12 fiber cable w/ Plenum jacket	$666.95

Table 4: Fiber Optic Cable Prices

4. LABORATORY TESTING – ACTUAL RESULTS

Regardless of what research or simulation indicates, the true test of both the performance of a technology and also the knowledge of how to properly apply that technology is borne out in laboratory testing. For this study, the key characteristics that are of interest are related to passing RF signals via a fiber optic link with minimal distortion and with a high level of immunity to EMI/RFI. A secondary constraint is that the fiber optic link should not be cost prohibitive. Due to the second reason related to cost, the laboratory testing was limited to commercial off the shelf (COTS) components as compared to laboratory grade components or components targeted for high performance AFL where cost is not a major concern.

Once all design criteria had been considered, an approach using the VCSEL optical transmitter was chosen and a VCSEL design implemented and tested. The VCSEL approach was chosen because of the following reasons:

1. Cost – VCSEL technology is relatively inexpensive.
2. Performance over temperature – datasheets insure operation over the industrial temperature range.
3. Ease of implementation – Circuitry for the TX/RX is not complex.
4. Performance – Component manufacturer's claim 2.5 Gbps performance.
5. Readily available components – many companies are manufacturing and selling VCSEL transmitters and PIN photoreceivers in multiple packages.

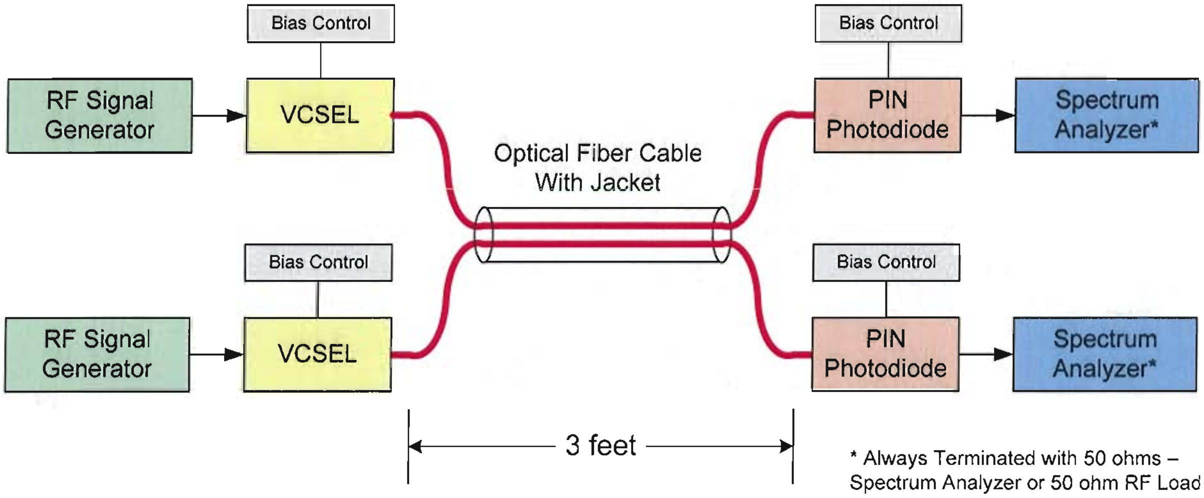


Figure 7: Implemented Test and Evaluation Concept

The test circuitry included two parallel fiber optic AFL paths, each consisting of a VCSEL, matching components, the optical receiver (a PIN photodiode), associated connectors and a 3 feet (1m) length of fiber optic cable. A block diagram of the implemented test set-up is shown in Figure 7. In testing the system, the following RF parameters were measured:

1. Scattering parameters (S21 and S12) from 100 MHz to 1.5 GHz. These scattering parameters allow the designer to verify system performance across the operational bandwidth.
2. Signal magnitude – Measuring the scattering parameters provided information on which frequencies provided the lowest overall loss for testing. A frequency of 1 GHz was chosen for the majority of testing.
3. Phase Noise – Phase noise measurements provide the designer with information pertaining to existing noise that may appear in the sidebands of a carrier frequency. Using the phase noise profile of the spectrum analyzer, it is possible to capture an image of the phase noise response for the system.
4. Frequency Isolation – This measurement, which is very important, measures the susceptibility of an RF system to be a carrier of RF energy for non-desired frequencies.
5. Intermodulation – This is another test of the fiber optic link to quantify the distortion produced by the process of transmitting and receiving an analog signal. Of particular interest is the signal level at which the passed signal starts to become non-linear to the point extraneous RF products are created.

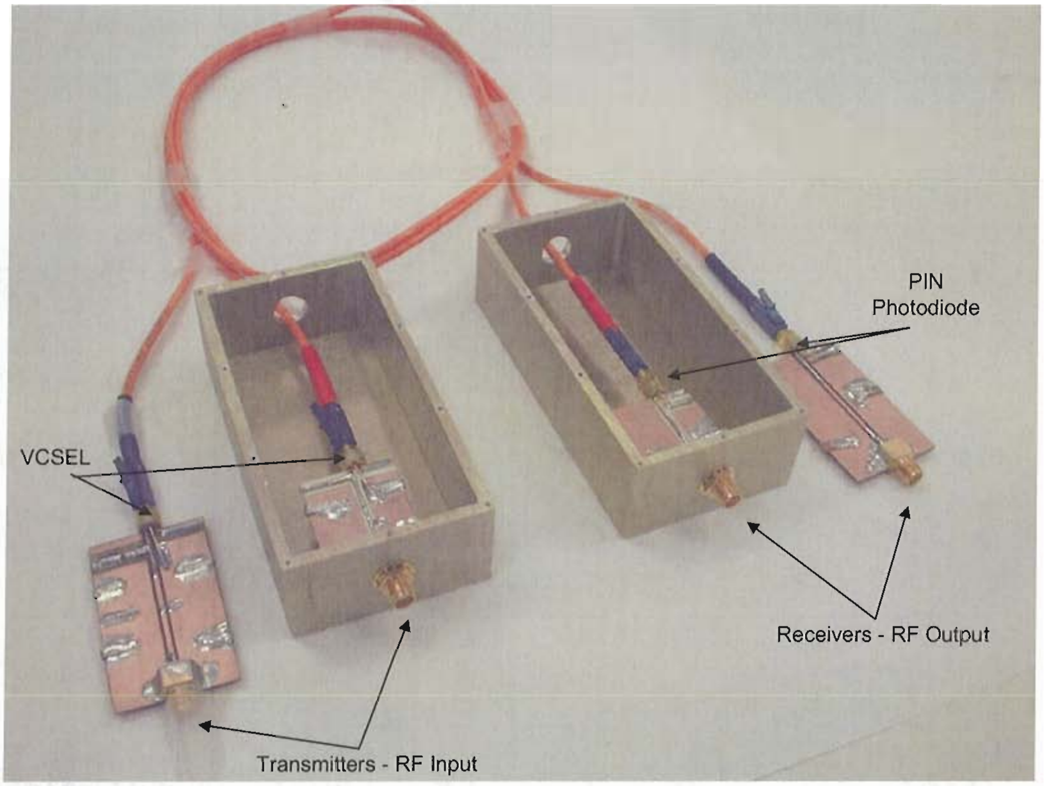


Figure 8: VCSEL Transmitter / Receiver Pairs with 1 meter of Fiber Optic Cable

Figure 8 depicts the two AFL systems used for laboratory measurements. A single AFL path is compromised of an SMA connector for applied RF signals, a 50 ohm impedance network, a VCSEL transmitter, the fiber optic cable, a receiving PIN Photodiode, and an SMA connector for the output RF signal.

SCATTERING (S) PARAMETERS

Scattering parameters, commonly called s-parameters, are an accepted, industrial standard methodology used for describing a unit under test (UUT) as a two port black box. S-parameters can accurately characterize the performance of a UUT when operating in a linear portion of its dynamic range. It also is quite useful in emulating and simulating systems by providing a mathematical model for the UUT.

A brief explanation of s-parameters follows. The UUT is characterized using a 2 port model based on a 50 Ω system. At each frequency, there are four s-parameters that describe the UUT's behavior. The four s-parameters are: S11, S12, S21, and S22. A simple explanation is that the S11 and S22 s-parameters quantize the relationship of the input and out, respectively, to a 50 Ω system. The S12 and S21 parameters indicate the attenuation or loss of a signal as it passes through the two-port UUT. S21 is for indicating forward gain (or loss) and S12 is for reverse isolation through the UUT.

Capturing s-parameters was accomplished by calibrating a Hewlett Packard 8753A Network Analyzer for the frequency band of interest. A single AFL path was then placed between the output and input ports of the network analyzer. The S12 and S21 response for the system is displayed in Figure 9. The S21 trace is the upper trace and shows that the gain (actually loss since the values are negative) varies with frequency. The measured loss varied between -2 dB to -10 dB in the frequency range of 100 MHz to 1 GHz. The loss then dropped to -20 dB from 1 GHz to 1.5 GHz. A point to note is that designs must take into account the frequency transmitted in order to account for loss.

The S12 trace is at the bottom of the plot and it shows reverse isolation around -60 dB across the 100 MHz to 1.5 GHz span. This is very respectable and superior to general purpose RF amplifiers, which have reverse isolation performance ranging around -20 to -40 dB.

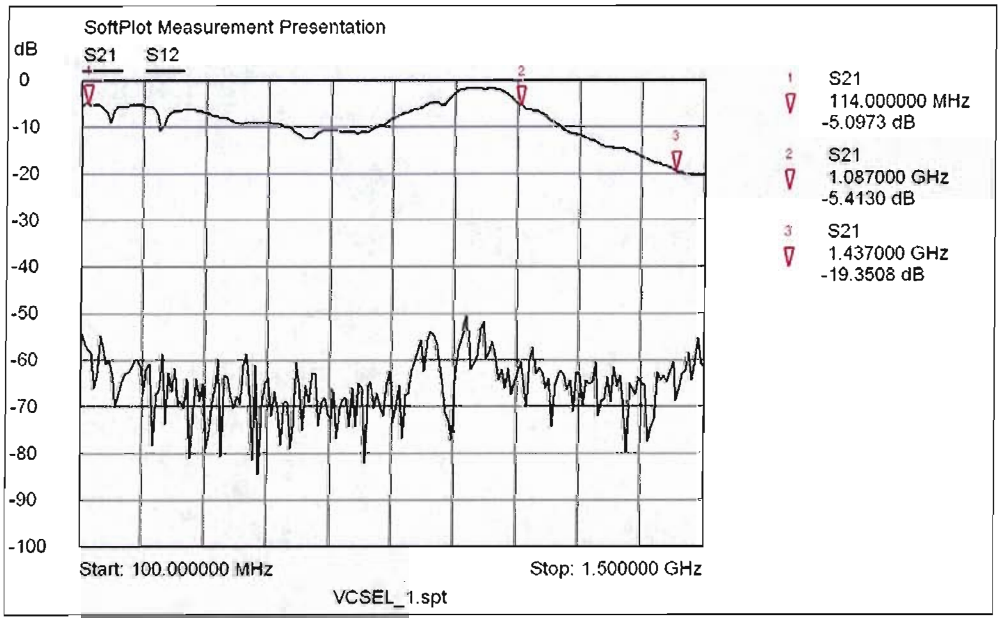


Figure 9: S12 and S21 Plot for VCSEL System

It was observed that modifying the drive current on the TX laser and RX PIN photodiode could improve the scattering parameter response. To level the gain response across a wide frequency band would be challenging; however, leveling the gain for narrowband frequencies would be much less difficult.

SPURIOUS RESPONSE

Spurious response was measured at 1 GHz. Figure 10 displays the resultant plot. The peak of the signal is approximately -10.5 dBm. A difference of six graticules or 90.28 dB (6 x 15 dB / graticule) was observed between the carrier and a spurious frequency component generated by the VCSEL.

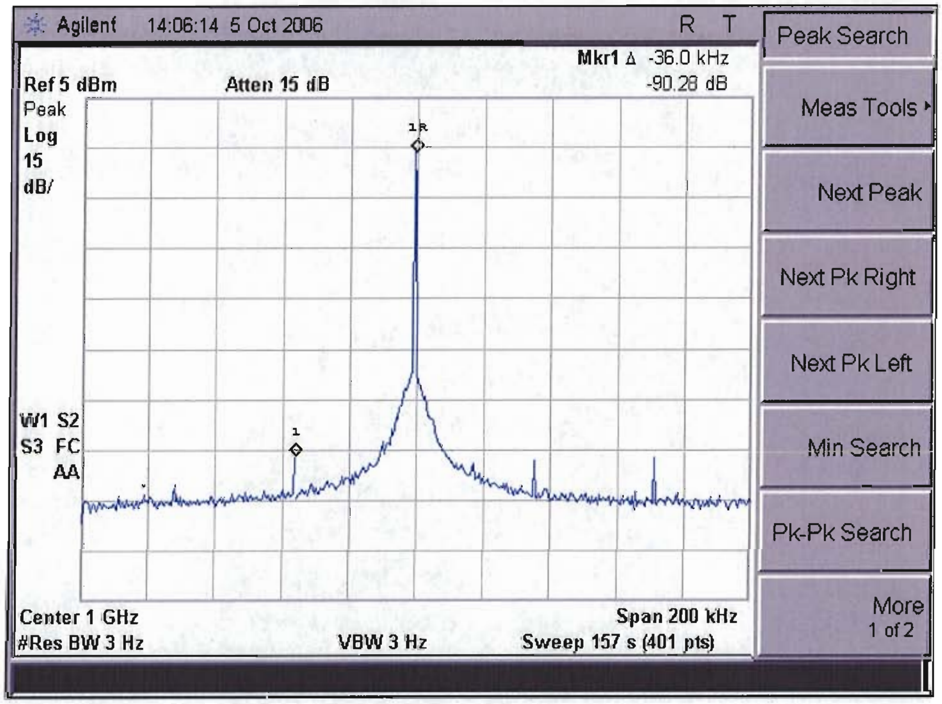
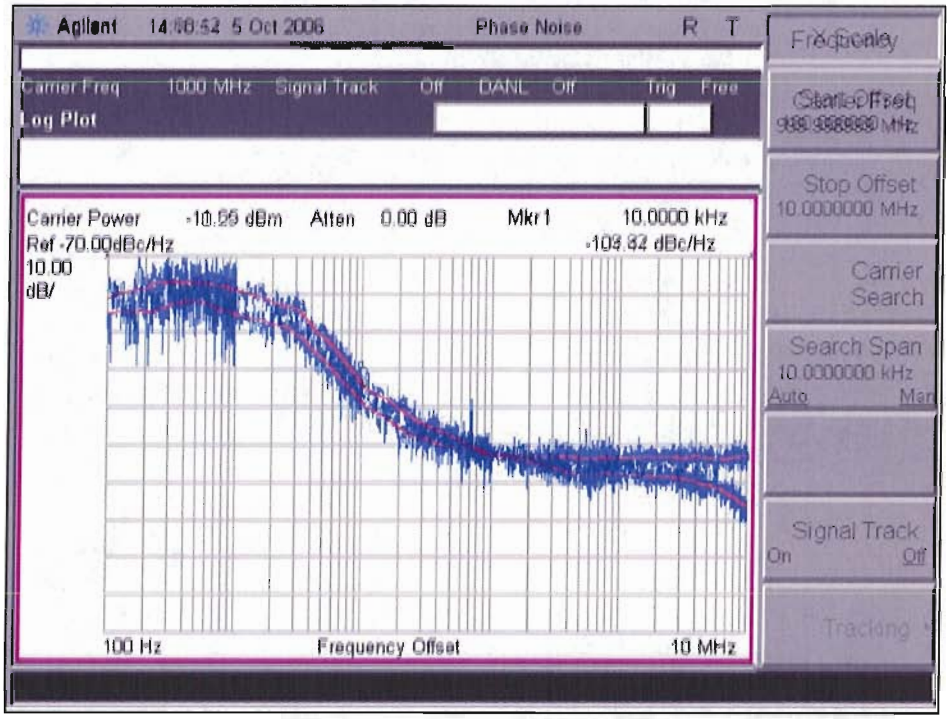


Figure 10: 1 GHz Signal Received Through Fiber Optic Link
(Note vertical scale is 15 dB/division)

EFFECTS ON PHASE NOISE

A very sensitive and effective measurement for determining any distortion created by a signal passing through a UUT is a phase noise measurement. This measurement carefully measures the noise power of a signal at various offsets from the carrier. Noise power levels of -80 dBc are easily measured. This corresponds to a power ratio between the offset noise and the carrier of 1 part in 100 million.

Phase noise was measured for both the test equipment and the device under test. In Figure 11, the plots are transposed to display the variation between the phase noise levels. The main take-away is that phase noise which goes though the fiber optic system does not degrade by more than 5 to 10 dB. Absolute phase noise for the fiber optic system is approximately -120 dBc/Hz at 50 kHz offset from the carrier. [The spike at approximately 60 kHz was determined to be a frequency component of the test equipment and is not a frequency component of the fiber optic system.]



14:58:52 5 Oct 2006

Carrier Freq 1000 MHz Signal Track Off DANL Off Trig Free

Carrier Power -10.59 dBm Atten 0.00 dB Mkr1 10.0000 kHz

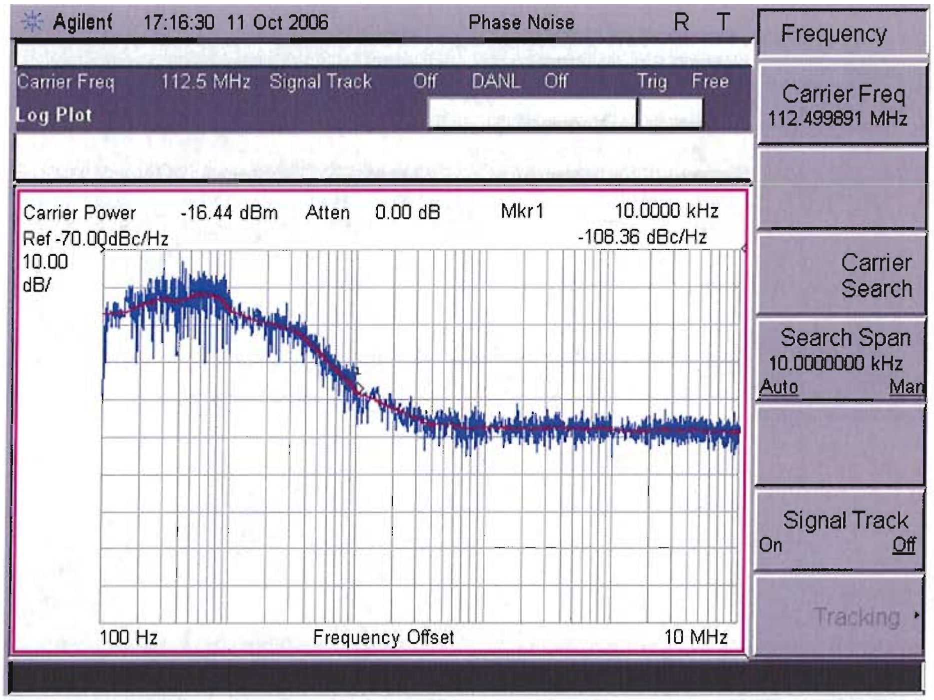
Ref -70.00dBc/Hz -103.84 dBc/Hz

Stop Offset 10.0000000 MHz

Search Span 10.0000000 kHz

Figure 11: Phase Noise at 1 GHz Showing Slight Difference from Laboratory Test Equipment

Additional phase noise data was taken for three frequencies of interest, 112.5 MHz, 1087.5 MHz, and 1435.5 MHz. The plots in Figure 12, Figure 13, and Figure 14 illustrate that the phase noise varies little across the three frequencies.


Agilent 17:16:30 11 Oct 2006 Phase Noise R T

Carrier Freq 112.5 MHz Signal Track Off DANL Off Trig Free

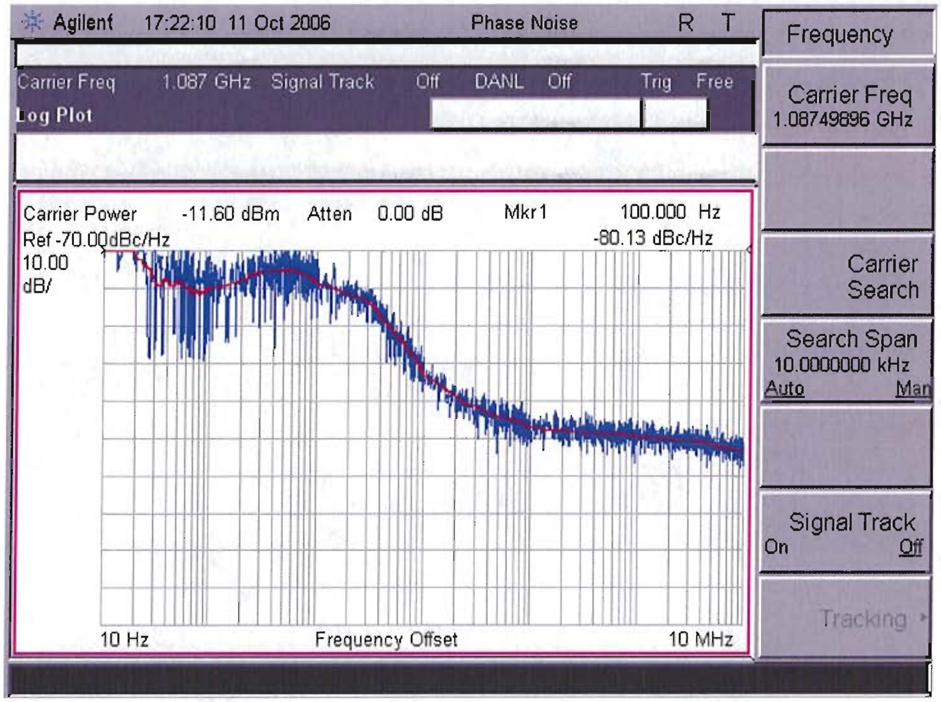
Log Plot

Carrier Power -16.44 dBm Atten 0.00 dB Mkr1 10.0000 kHz

Ref -70.00dBc/Hz -108.36 dBc/Hz

10.00 dB/

Figure 12: Phase Noise Plot at 112.5 MHz


Agilent 17:22:10 11 Oct 2006 Phase Noise R T

Carrier Freq 1.087 GHz Signal Track Off DANL Off Trig Free

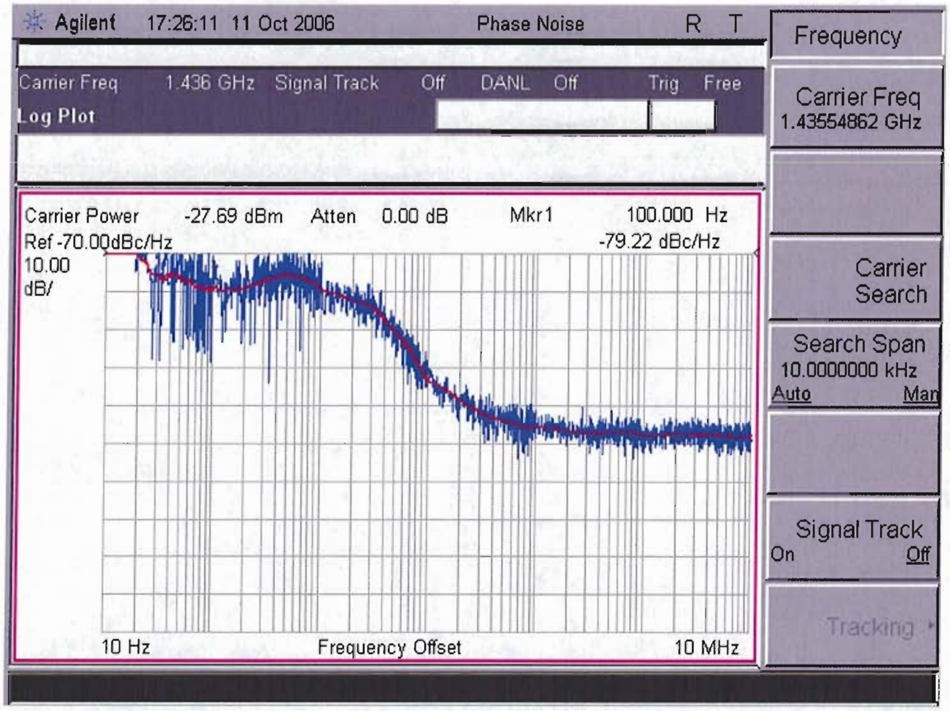
Log Plot

Carrier Power -11.60 dBm Atten 0.00 dB Mkr1 100.000 Hz

Ref -70.00dBc/Hz -80.13 dBc/Hz

10.00 dB/

Figure 13: Phase Noise Plot at 1087.5 MHz



17:26:11 11 Oct 2006

Carrier Freq 1.436 GHz Signal Track Off DANL Off Trig Free

Carrier Power -27.69 dBm Atten 0.00 dB Mkr1 100.000 Hz

Ref -70.00dBc/Hz -79.22 dBc/Hz

10.00 dB/

Carrier Freq 1.43554862 GHz

Search Span 10.0000000 kHz Auto Man

Signal Track On Off

Figure 14: Phase Noise Plot at 1435.5 MHz

CIRCUIT ISOLATION

Another set of measured data represents the frequency isolation between two RF CW signals. Isolation between circuits is important in preventing spurious RF energy from getting into the signal path. It is measured by driving a signal into one of the signal paths shown in Figure 7 and measuring the other AFL signal path for any stray RF energy at that frequency. This will indicate the amount of energy that in some way leaks across the two AFL paths.

Frequencies injected were 1.0015 GHz and 1.002 GHz. The plots display frequency isolation at 88.63 dB and 90.91 dB respectively. The frequency isolation measurements prove that relatively good isolation can be achieved using the VCSEL and PIN photodiode. Additionally, it is believed that even greater isolation can be achieved by isolating power supply lines, filtering potential RF paths, and implementing other RF design lessons learned from previous designs.

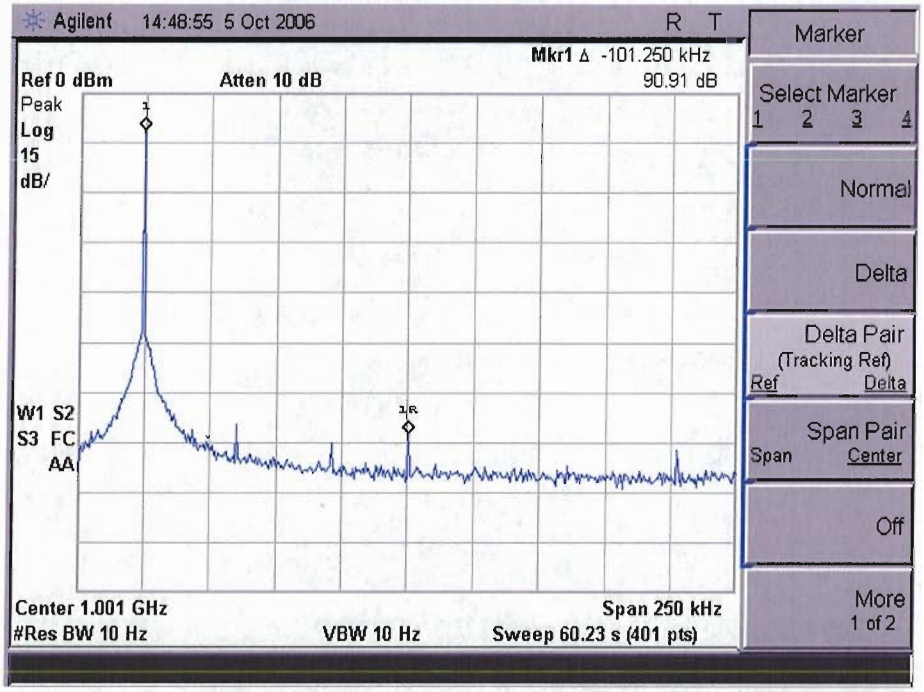


Figure 15: Isolation VCSEL 1 to 2 (Note: Magnitude is 15 dB/division)

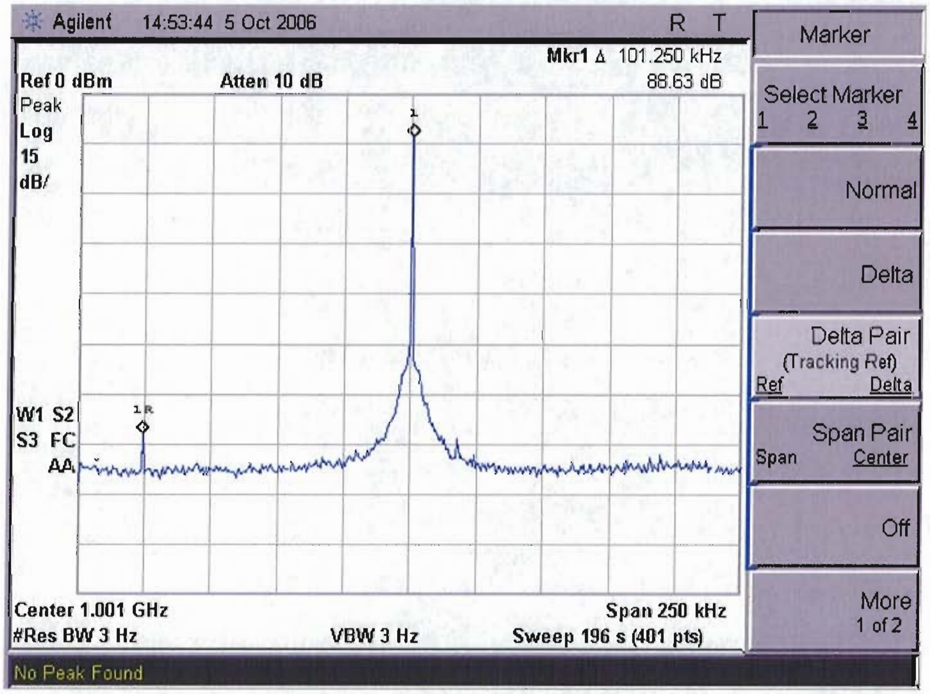


Figure 16: Isolation VCSEL 2 to 1 (Note: Magnitude is 15 dB/division)

It is speculated that these isolation plots do not truly represent the isolation between two fiber optic cables. In theory, the isolation between two or more optical fibers is infinite. However the causal systems are still subjected to the potential for electromagnetic interference at the RF/Optical switch point. Any stray radio frequency signal has the potential to be modulated and transmitted down the opposite channel if the RF circuitry is not properly shielded.

INTERMODULATION CHARACTERIZATION

Intermodulation distortion (IMD) is the generation of unwanted sum and difference frequencies when two or more signals are amplified in a non-linear device.*[18]* The degree to which the device is non-linear is an important design parameter as the effect of the non-linearity is un desired RF energy. Intermodulation characterization provides an indication of the level of signal an optical transmitter/optical receiver can pass with high fidelity.

Figure 17 and Figure 18 display the measured results for two-tone, third-order intermodulation. This measurement consists of injecting two tones at the input to the UUT and measuring the ratio of the passed tones to the RF products created by non-linear behavior in the UUT. The two input tones are spaced 39.6 MHz apart. The undesired side-tones created are at spacings equivalent to the spacing between the two input tones. Third order intercept point (IP3) was measured using the two-tone intermodulation set-up. The IP3 is a standard parameter used in RF design to predict the degree of non-linearity in a UUT.

Intermodulation was measured and double-checked by decreasing input power from 0 dBm to -20 dBm in 5 dB steps. Figure 17 and Figure 18 represent 0 dBm and -20 dBm applied, with output of -15 dBm and -33 dBm, respectively. The delta between inter-modulation signals decreases from 17.71dB to 54.77 dB.

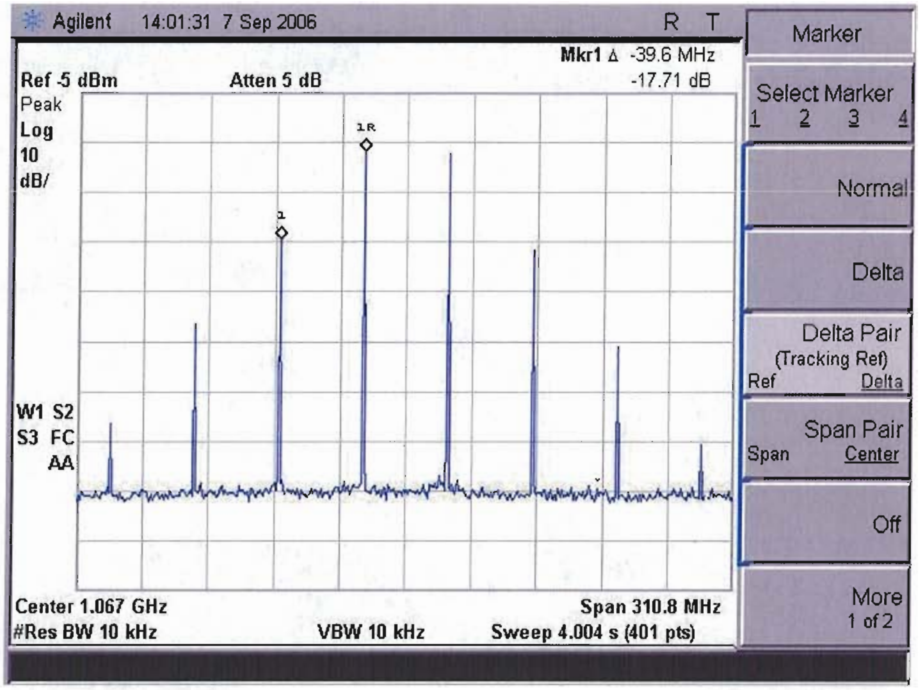


Figure 17: Intermodulation at 0 dBm Input

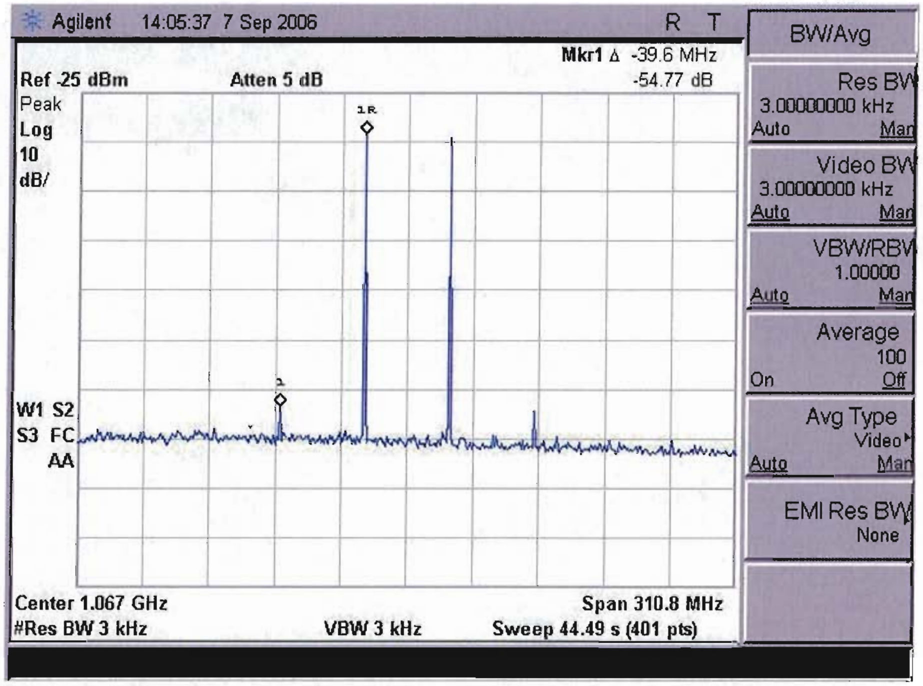


Figure 18: Intermodulation at -20 dBm Applied

The equation for calculating the Input Intercept Point (IP3) from the two tone IMD test is:

Equation 1:

$$I_n \text{ (dBm)} = S/(N-1) + P \qquad \text{(N}^{th}\text{ Order Intercept Calculation)}$$

Where :

	I_n	is the Nth order intercept point in dBm
	S	is the relative suppression from the carriers in dB
	N	is the order of the intermodulation product
	P	is the power level of the carrier tones, in dBm

Equation 2:

$$I_3 \text{ (dBm)} = S/(3-1) + P \qquad \text{(3}^{rd}\text{ Order Intercept Calculation)}$$

Using the he 3rd order intercept (IP3) of Equation 2 with the measured plots of Figure 17 and Figure 18, the IP3 is -6 dBm and -5.5 dBm respectively. These two measurements closely agree, even with very different tone levels. This provides confidence for the measurement.

It is observable from the data above that IMD products can significantly be reduced by decreasing the power applied to the VCSEL, as is the result in any amplifier circuit.

RF POWER OUTPUT VS. RF POWER APPLIED

Figure 19 depicts the power output for the three frequencies of interest as well as the frequency that had the best overall performance according to S21 measurements given in Figure 9. System performance is linear until power applied is greater than -5 dBm. The VCSEL begins to go into compression at approximately -10 dBm. This constraint on the highest signal that can be passed linearly is manageable by adding extra RF gain at the receiver end of the AFL. This allows lower level signal to be transmitted across the fiber and then amplified to the required level once the optical receiver has converted the modulated light back to an electrical signal.

There are two ways to enhance system performance. One is by matching input/output components for the transmitter and receiver circuits. The second way is by changing the sourced current to the transmitting VCSEL and the receiving PIN Photodiode.

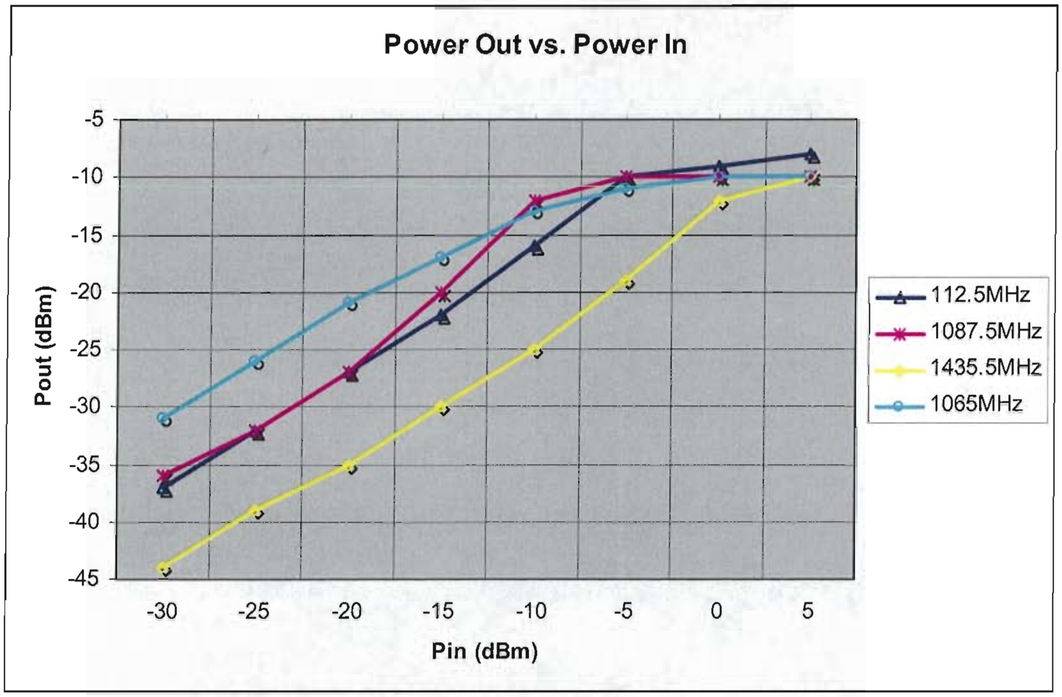


Figure 19: RF Power Out vs. Power Applied

5. PRINTED CIRCUIT BOARD IMPLEMENTATION – DESIGN CONSIDERATIONS

CHALLENGES

The challenges involved in implementing fiber optic signal paths on PCBs are many and varied. The key challenges are listed below. An important criterion is to provide the high performance capabilities of a fiber optic AFL while maintaining the low cost and small form factor needed for PCB utilization. Trends indicate that these two challenges are being addressed by industry.

- Size and Miniaturization
- EMI associated with TX and RX (not with the fiber)
- Phase noise performance floor
- Intermod
- Limited dynamic range
- High speed interface circuitry
- Splitting the optical signal using fiber; as in 3 dB splitter
- Choosing the operating wavelength

MINIATURIZATION

The method of miniaturization *[11]* displays the ability to develop small form-factor VCSEL systems at a low cost. The authors were able to develop a 7mm^2 surface mount VCSEL system for short-haul (< 300 meters) communications. Additionally, integrated circuit designers are experimenting with the application of VCSEL technology within the individual component. It may be possible in the near future to have an RF amplifier that drives a VCSEL within the same device, such as a multi-chip module *[12]*. This could significantly facilitate fiber optic interconnects between devices on the same PCB.

EMI ASSOCIATED WITH RX AND TX RF (NOT FIBER)

The optical fiber is theoretically not susceptible to EMI concerns. Applications using fiber should have no EMI concerns; both susceptibility issues and as an emitter. This study has shown this to be true regarding the optical fiber, however the optical transmitters and the optical receivers are, respectively, EMI emitters and EMI susceptible. Using optical fiber can reduce EMI concerns but good, sound RF layout is still required to address the optical transmitters and optical receivers. The optical receivers have significant gain and demand specially care by shielding and layout.

PHASE NOISE FLOOR

There is an artificial phase noise floor created as part of the process of converting electrical signals to modulated light and re-converting back again. This phase noise floor is well above thermal noise but still low enough that it can be accommodated by many systems. The system requirements must take into account this phase noise floor and appropriate design decisions made accordingly. The phase noise floor is comparable to high speed digital integrated circuits.

INTERMOD

The challenges with intermodulation is that the VCSEL characterization indicated that the intermodulation performance is less than that of what typical RF driver circuits are capable of providing. A work-around is to manage the RF levels at the fiber optic interfaces to mitigate intermodulation within the system. This may require a more gain at the receiver side of the link to manage the performance of intermodulation and spurious generation.

DYNAMIC RANGE

The dynamic range of the fiber optic AFL is not as large as typical RF systems and the challenge is to design around this limitation. There are applications that appear to be good fits, such as using for distributing Local Oscillator (LO) signals and clocks. These are higher level signals that do not demand high dynamic range.

An alternate method of designing around the dynamic range is use high dynamic range circuits on both the transmit and receive ends of the AFL and employ a "compressed" dynamic range for over the AFL fiber optic cable.

HIGH SPEED INTERFACE CIRCUITRY

Research into fiber optic communication integrated circuits led to the discovery of a wide range of 2.4 Gbps and higher throughput devices. All of the major semiconductor manufacturers design and fabricate high speed communication integrated circuits used in fiber optic systems. Some of the devices identified are: ECL/PECL (Emitter Coupled Logic / Positive Emitter Coupled Logic) Converters, limiting amplifiers, laser drivers, receivers, and optical module assemblies that are used in the telecommunication industry. For example, the MAX3975 is a compact, 3.3V VCSEL driver that can directly modulate a VCSEL up to 10.7 Gbps. Form factor is small and the device is cost effective at $28.00 per integrated circuit (IC).

SPLITTING THE FIBER SIGNAL

Splitting fiber optic signals can be complex and expensive. The methods necessary for interconnection of multiple fibers into one include coupling, tapping, switching, and wavelength-division multiplexing. Mechanically splitting optical interconnects will be briefly covered.

Fiber optic splitters are the simplest optical coupling systems. Operationally, a fiber optic splitter will have at least three ports; one input port (also known as the common fiber) and two output ports. A split ratio specifies the amount of optical power to be transmitted into each output port. The user or manufacturer can state the splitting ratio for the coupling system. Multiple ratios exist that can meet optical power requirements at the output. This may allow for equal distribution of optical power to multiple receivers, or allow for different optical power levels to be received at the output. Some common split ratios are listed in Table 5.

Split Ratio (%)	Typical Insertion Loss (dB)
50/50	3.1/3.1
45/55	3.6/2.7
40/60	4.1/2.3
35/65	4.7/2.0
30/70	5.4/1.7
25/75	6.2/1.4
15/85	8.4/0.8
10/90	10.2/0.6
5/95	13.2/0.4
10/45/45	10.5/4.0/4.0
20/40/40	7.3/4.5/4.5
30/35/35	5.4/4.8/4.8
40/30/30	4.1/5.4/5.4
50/25/25	3.1/6.2/6.2
60/20/20	2.3/7.2/7.2
70/15/15	1.7/8.5/8.5
80/10/10	1.0/10.5/10.5
25/25/25/25	6.4/6.4/6.4/6.4

Table 5: Conversion Comparison of Split Ratio Versus Typical Insertion Loss (dB) ***[19]***

Splitting optical fibers has drawbacks. The insertion loss for the system increases as additional fibers are added at the output, and can also degrade with the desired split ratio. Additionally, the price for optical interconnect systems can be prohibitive. Timbercon, a manufacturer of optical interconnect systems, produces couplers and splitter for the 800 nm – 1300 nm optical wavelengths. A 1-to-2 single mode fiber optic splitter with ST connectors was purchased from Timbercon for $158.00.

6. WHAT THE OPPORTUNITY HOLDS – POTENTIAL APPLICATIONS

Based upon research, it is feasible to state that a radio frequency distribution system can be comprised of a simple VCSEL and PIN Photodiode fiber optic circuit. The circuit could remote radio frequency signals up to several meters, and could be implemented into a current PCB design, or could be implemented into modules of the caliber that is available on the open market. The system would be easy to implement and could produce greater frequency isolation between channels, isolate RFI, and reduce the need for shielding.

There are multiple applications that take advantage of the capability provided by optical fiber communication. Three straight-forward examples are provided for discussion. Many more are possible and are only limited by the user's imagination.

The first example to be discussed is shown in block diagram form in Figure 20. The application takes advantage of optical fiber's low susceptibility to EMI issues. A sensitive RF signal is distributed across a printed circuit board to several RF sub-circuits. The RF sub-circuits are co-located with high speed digital sub-circuits. The optical fiber will not act as a conduction path for any digital noise. It also will not pick up any radiated digital signals. This allows routing of the fiber in close proximity to the high speed sub-circuits.

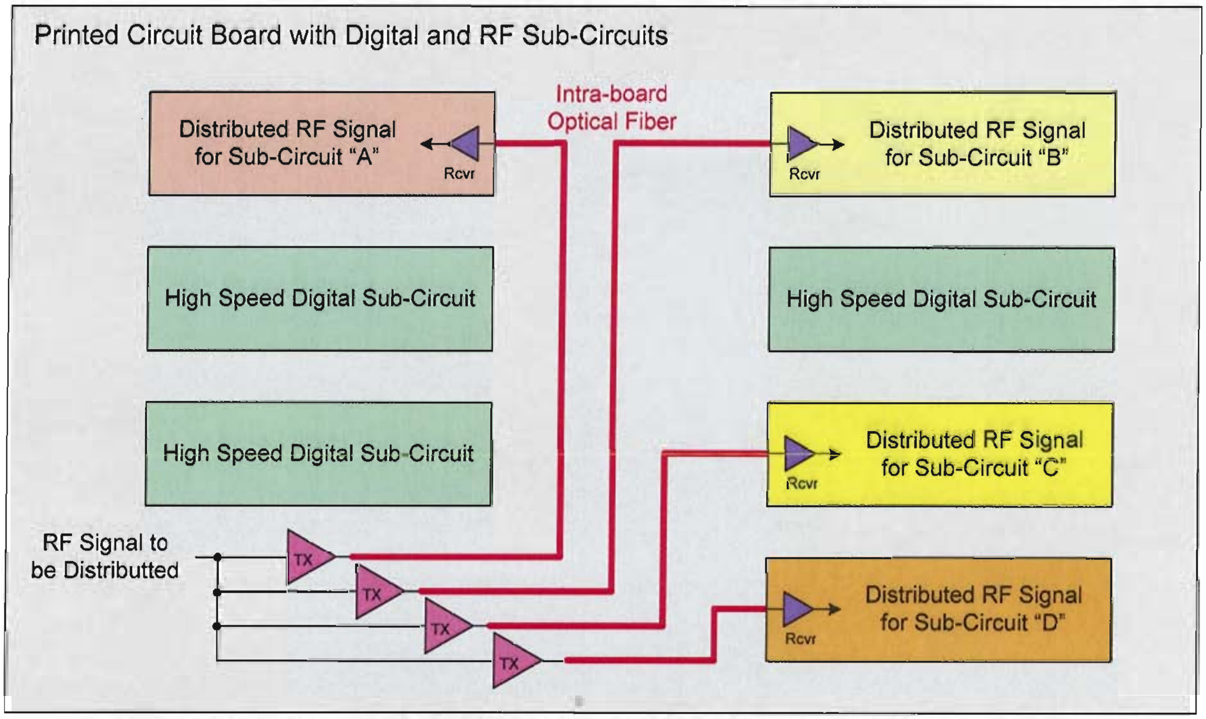


Figure 20: Application Example 1 - Distributing RF Across PCB With RF and Digital Sub-Circuits

The second application is shown in Figure 21 and depicts the case where two RF signals are sent to another PCB through a single optical fiber. The two RF signals at different frequencies are combined by commonly available RF design techniques and then converted into modulated light by the optical transmitter (labeled as TX in Figure 21). The optical receiver on Printed Circuit Board 'B' converts the modulated light back into two RF signals and a frequency selective circuit separates the two RF signals.

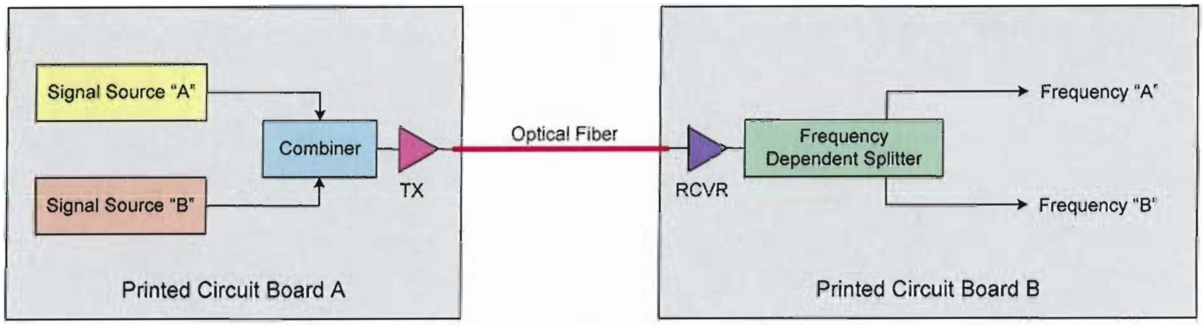


Figure 21: Passing Two RF Signals Between Printed Circuit Boards

The third application to be discussed is the issue where many sensitive RF signals are required to be distributed to different modules within the same system. In the block diagram of Figure 22, the RF signals are labeled as local oscillators. Figure 22 has a total of three different Local Oscillators being distributed to two modules. One of the modules receives two different local oscillators.

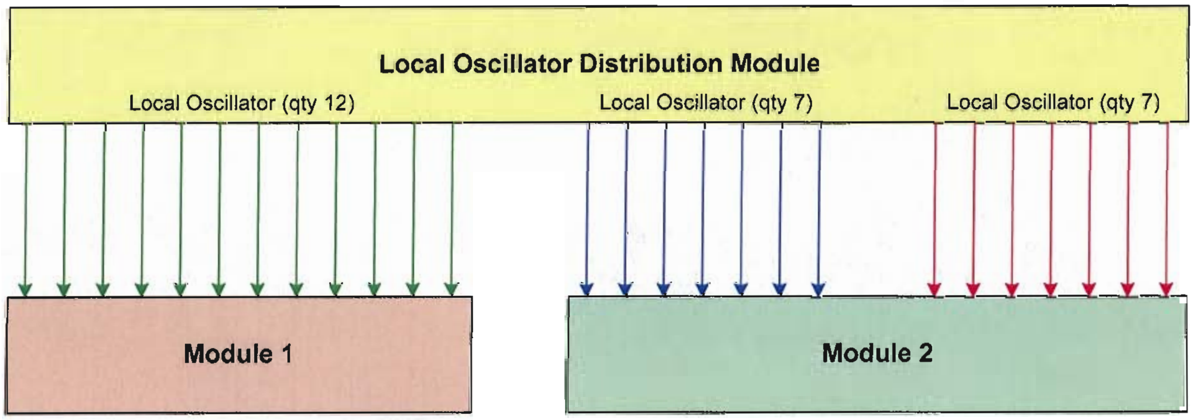


Figure 22: Distributing Multiple RF Signals to PCBs within a System

7. FUTURE RESEARCH AND DEVELOPMENT

Additional items to investigate include higher throughput transmitters and receivers for operational frequencies beyond 5 GHz, implementation of multiple transmitters and receivers on a single printed circuit board for more thorough frequency isolation measurements, and connecting the prototyped circuits up to an operational system and verify functionality. Investigating performance on operational systems could only assist in proving out concepts and could lead to measures of effectiveness in operational capability. Knowing the exact limitations of transmission length, isolation between transmission lines, phase noise floor performance and receiver sensitivity would allow for system optimization and could lead to a new line of inexpensive RF-over-Fiber Optic transceivers that are low cost yet yield high performance.

8. CONCLUDING REMARKS

Initially, it was thought, that a single-mode, 1310 nm direct feedback laser system would be necessary to achieve a radio frequency link over fiber optic cable. This was the initial assumption after a short time at researching the state-of-the-art for fiber optics. This system would have been expensive to implement due to the cost of DFB and Fabry-Perot lasers. It was only after VCSEL lasers were investigated and their high performance for low cost was discovered that a feasible and economical method of distributing RF signals through a fiber optical cable was realized. **It has been proven, by this study, that an inexpensive VCSEL system can produce usable results in distributing RF over Fiber.** The cost effectiveness of VCSEL technology drives the potential for this application.

9. ACKNOWLEDGEMENTS

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