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## The Fastest PAM-4 Signal Ever Generated

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## Abstract

The fastest electrical PAM-4 signal is demonstrated. The technology behind the generation of this signal along with the acquisition of the signal is discussed along with the motivation for generating signals like this in optical communications research.

## Author(s) Biography

**PETER J. PUPALAIKIS** received the B.S. degree in electrical engineering from Rutgers University in 1988. He joined LeCroy Corporation (now Teledyne LeCroy) in 1995 where he is currently Vice President, Technology Development, managing digital signal processing development and intellectual property. His interests include digital signal processing, applied mathematics, signal integrity and RF/microwave systems. Prior to LeCroy he served in the United States Army. Mr. Pupalaiakis holds forty-two patents. He is an IEEE fellow for contributions to high-speed waveform digitizing instruments. He is a member of Tau Beta Pi, Eta Kappa Nu and the IEEE signal processing, instrumentation, and microwave societies and serves on the DesignCon TPC and the industry advisory boards for ECE and the Rutgers ECE department.

**XI CHEN** received the B.E. degree in telecommunication engineering from National University of Defense Technology, Changsha, China, in 2008. She received Ph.D. degree from The University of Melbourne, Melbourne, Australia, in 2012. She worked in Huawei Ltd. in 2008, on 3G wireless network construction. From 2013 to mid-2015, she worked as a Research Fellow in The University of Melbourne, conducting research on optical fiber transmission. Since late 2015, she joined Nokia Bell Labs and her current research interests include advanced digital signal processing for high speed optical subsystems and fiber transmission.

**SETHUMADHAVAN CHANDRASEKHAR** received the B.Sc., M.Sc., and Ph.D. degrees in physics from the University of Bombay, Bombay, India, in 1973, 1975, and 1985, respectively. He joined the Tata Institute of Fundamental Research, Bombay, India, as a Research Scholar in 1975 and then became a Research Associate in 1979. He had been engaged in research on Si-SiO interface studies, complementary metal-oxide-semiconductor integrated circuits, ion implantation, charge-coupled devices, and laser recrystallization. In 1986, he joined AT&T Bell Laboratories (now called Lucent Technologies, Bell Laboratories), Crawford Hill Laboratory, Holmdel, NJ, as a Postdoctoral Member of Technical Staff. Since then, he has been working on III-V compound semiconductor devices for optoelectronic applications, primarily waveguides, photodetectors, heterojunction phototransistors, and heterojunction bipolar transistors (HBTs). He became a permanent Member of Technical Staff in May 1992. He has been engaged in high-speed optoelectronic integrated circuits (OEICs), integrating p-i-n photodetectors and laser diodes with HBTs, for long-wavelength optical communications. Since January 1999, he has been responsible for forward-looking research in wavelength-division-multiplexing (WDM) optical networking. He has set up an optical networking testbed for investigation of optical networks comprising add/drop multiplexers, optical cross connects, and wavelength-selective switching. His current interests include 40-Gb/s transport and networking, modulation formats, and electronic signal processing at the receiver. He is currently a Distinguished Member of Technical Staff. He holds 13 U.S. patents. Dr. Chandrasekhar is a Member of the IEEE Lasers & Electro-Optics Society (LEOS). He has been Associate Editor of IEEE PHOTONICS TECHNOLOGY LETTERS since 1998. He has been member of the technical program committees of the International Electron Devices Meeting (IEDM), the Device Research Conference (DRC), and the Optical

Fiber Communications (OFC) conferences. He was awarded the IEEE LEOS Engineering Achievement for 2000 jointly with two other awardees for his contribution to OEIC photoreceivers and the Optical Society of America (OSA) Engineering Excellence Award for 2004 for his contributions to OEICs and WDM systems research.

**SEBASTIAN RANDEL** received the Ph.D. degree in electrical engineering from Technische Universität Berlin, Berlin, Germany, in 2005, for his study on nonlinear optical time division multiplexing transmission. He is a Member of the Technical Staff at Bell Laboratories, Alcatel-Lucent, Holmdel, NJ. He is currently involved in the research on ultrahigh capacity optical transmission systems. From 2005 to 2010, he was a Research Scientist at Siemens AG, Munich, Germany, where he was involved in physical layer aspects of optical access, in-house, automotive, and industrial networks. Dr. Randel was a Founding Chairman of the DKE Working Group Polymer Optical Fiber and is a member of the Association for Electrical, Electronic and Information Technologies/Information Technology Society.

**GREG RAYBON** received the B.S. degree in Electrical Engineering from Pennsylvania State University in 1984 and the M.S. degree in Material Science from Stevens Institute of Technology, Hoboken, NJ, in 1989. From 1984 to 1985, he was a Product Engineer with National Semiconductor Corporation where he worked on IC fabrication. He joined the Photonic Networks Research Department at AT&T Bell Laboratories, Holmdel, NJ, in 1985 and he is currently Member of Technical Staff in Bell Laboratories, Lucent Technologies. His research has been focused on high-speed optical communications systems beginning in 1988 with an 8 Gbit/s OTDM transmission system and evolving to a 160 Gbit/s system in 1999. To achieve these results, he has worked on components and subsystems that advance the speed and functionality of optical systems. Complex photonic integrated circuits such as laser arrays, mode-locked lasers and wavelength converters have been studied. His current research continues to examine new ideas that can extend the reach and increase the capacity of any optical system.

**ANDREW ADAMIECKI** was born in Kozięglowy, Poland, in 1955. He received the B.S. and M.S. degrees in electrical engineering from the Silesian Technical University, Poland in 1981 and 1983, respectively. From 1986 to 1991 he was a Senior RF-Communications Engineer with Ademco, a Division of Pittway Corporation, Syosset, New York working on Direct Sequence Spread Spectrum techniques for commercial security system application. From 1991 he joined AT&T Consumer Product Division working on cellular phones architectures and design for TDMA, CDMA and GSM standards. He is now a Member of Technical Staff of Bell Labs Lucent Technologies, Photonics Research Department. His current work includes microwave and high speed electronics circuit and subsystems design, development and analysis.

**PETER J. WINZER** received the Ph.D. degree in electrical engineering from the Vienna University of Technology, Vienna, Austria, in 1998. Supported by the European Space Agency, he investigated space-borne Doppler lidar and laser communications using high-sensitivity digital modulation and detection. In 2000, he joined Bell Laboratories, Alcatel-Lucent, Holmdel, NJ, where his research focused on many aspects of fiber-optic networks, including Raman amplification, optical modulation formats, advanced optical receiver concepts, digital signal processing and coding, as well as on robust network architectures for dynamic data services. He demonstrated several high-speed and high-capacity optical transmission records from 10 to 100 Gb/s and beyond, including the first 100G and the first 400G electronically multiplexed optical transmission systems and the first field trial of live 100G video traffic over an existing carrier network. In 2007, he became the Distinguished Member of Technical Staff, Bell Laboratories and since 2010 he has been the Head of the Optical Transmission Systems and Networks Research Department. Dr. Winzer is a Member of the Optical Society of America. He has widely published and patented and is actively involved in technical and organizational tasks with the IEEE Photonics Society and the OSA.

# Introduction

EARLY IN 2016, researchers at Nokia Bell Labs in Crawford Hill, New Jersey teamed up with engineers at Teledyne LeCroy to set out to produce the worlds fastest arbitrary waveform generator ever produced. The Bell Labs researchers need very high-speed signal generators in their research in to high-speed, long-haul optical communications systems. In 1996, the first 1 Tb/s optical transmission on a single fiber was demonstrated [1, 2, 3] and recently, single carrier 1 Tb/s optical communication has been demonstrated [4]. In recent years, as a result of research performed by facilities like Nokia Bell Labs, more and more signal was crammed into a single fiber.

In optical communications, the basic idea, is to generate electrical signals, convert these to optical, and to mix these signals up such that they occupy a spectrum about a carrier signal which is a single wavelength of light. Many of these wavelengths are utilized in a single fiber to produce staggering data rates. Today, the theoretical upper limit is thought to be 38.5 Tb/s over a single fiber [5]<sup>1</sup>. Mostly, the transmission schemes use multiple wavelengths of light and per wavelength, use complex modulation schemes like dual polarity (DP)-quadrature phase shift keying (QPSK). So while there are multiple dimensions of the communications problem, it basically distills down to how many wavelengths can one utilize and how much data can be transmitted per wavelength.

While optical communications is a fascinating and fantastic field that enables all of our extreme data usage today, it still all starts and ends as electrical signals. At the transmitter, data is coded and modulated prior to its conversion to light, and at the receiver an optical-to-electrical (O/E) converter is utilized to convert the optical signal back to electrical for conversion to digital codes through the use of an analog-to-digital converter (ADC).

In the past, let's say a decade ago, the optical signal was essentially generated by turning light on and off, much like the electrical non-return-to-zero (NRZ) signal we are all familiar with. This communication scheme is simple, and is still used on short-haul networks. Inasmuch as the test and measurement field is concerned, this scheme greatly simplified the test equipment required and the test methodologies employed, especially at the receiver. For NRZ type signals, it is often possible to determine the signal quality using an equivalent time oscilloscope (usually referred to as a *sampling* scope). Sampling oscilloscopes are much simpler, and offer much higher bandwidths at a more reasonable price than the real-time oscilloscope.

With the advent of much more complex modulation schemes employed in standards like 100 Gb real-time oscilloscopes (usually referred to as a digital storage oscilloscope (DSO)) became an absolute must for testing the waveforms at the receiver and arbitrary waveform generators became an absolute must for generating signals. Today, oscilloscopes with bandwidths up to 100 GHz are available (manufactured by Teledyne LeCroy), but the speed of the arbitrary waveform generator (AWG) has lagged and is currently available from Keysight with a bandwidth and sample rate of 32 GHz, 92 GS/s. Since the oscilloscope end bandwidth need has been satisfied for now (in fact the oscilloscope bandwidth needs exceed the optical receiver technology currently in 2016 [6] , it is a goal for optical research to have an AWG with corresponding speeds. And that is how it all started.

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<sup>1</sup>It is difficult to give a true number for per wavelength upper limit, as the limit will depend on other wavelengths (wavelength spacing, etc). One theoretical estimation is shown in the reference (Fig. 38). The max. spectral efficiency is 8.8 bits/s/Hz for 500-km transmission. This is the limit per one fiber. Translating this spectral efficiency to capacity would be 38.5 Tb/s (=8.8 bits/s/Hz \* 4375 GHz). The 4375 GHz is the entire C-band window (where optical amplification is easy).

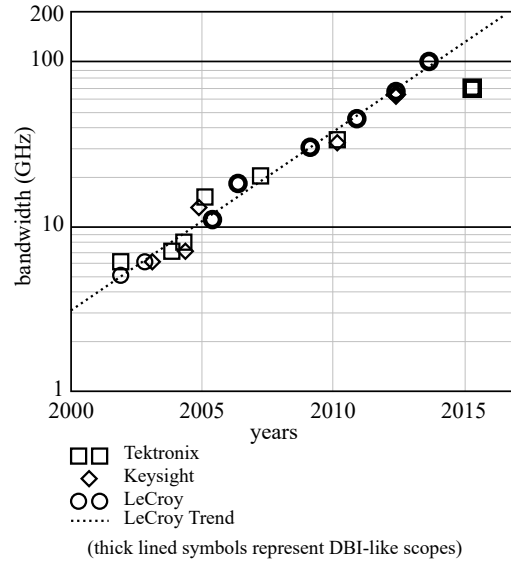


Figure 1: Oscilloscope Bandwidth Trend

## Digital Bandwidth Interleaving (DBI)

In the early part of this century, the battle between oscilloscope manufacturers was fierce with everyone trying to outdo the other for bragging rights on speed. To a smaller company, like LeCroy, it seemed impossible to keep pace.

In Figure 1 we see the progression of oscilloscope bandwidth over time for real-time scopes. This plot shows only scope introductions that represent the highest bandwidth scope from each of the three high-end vendors. Here we see a steady log-linear progression that is shown as the line marked *LeCroy Trend* which is the trend considering only scopes manufactured by Teledyne LeCroy - but which is fairly representative of the entire data set. The trend indicates an average yearly increase in bandwidth of approximately 28 percent which amounts to a doubling of bandwidth every 2.8 years. While the plot covers only the first decade of this century, this trend has been fairly constant for the last thirty five years. This is the Moore's law [7] of oscilloscopes.

in 2002 LeCroy invented digital bandwidth interleaving (DBI) [8] which enabled the company to produce very high bandwidth scopes and in 2006, produced the first DBI scope, the SDA11000 at 11 GHz bandwidth and 40 GS/s and since that time, all of LeCroy's highest bandwidth oscilloscopes are based on DBI technology [9, 10], which I will explain, and as a matter of fact, all of the highest-end products produced by the three oscilloscope manufacturers you are familiar with utilize techniques that I will refer to as DBI-like [11, 12]. The DBI-like scopes are shown Figure 1 with thick lined symbols and you can see that above 40 GHz, all of the highest bandwidth oscilloscopes are DBI-like.

DBI is a straightforward concept in theory, and rather complicated in practice. A DBI architecture that utilizes this traditional hardware is shown in Figure 2. In this design, three 36 GHz, 80 GS/s scope channels are utilized. The scope channels are combined with a microwave front-end and a digital signal processing (DSP) back-end. The combination of channel resources is common in oscilloscope designs and is often selectable by the user.

The microwave front-end shown stylistically in Figure 2 consists of a multiplexer that separates the

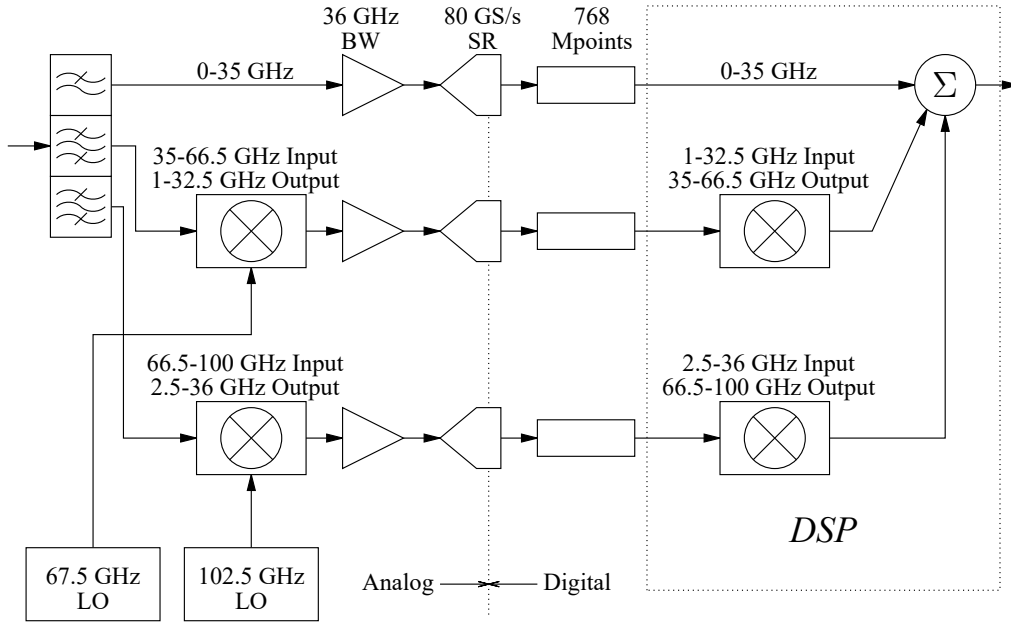


Figure 2: 100 GHz Oscilloscope Block Diagram

incoming signal into multiple frequency bands feeding multiple down-converters to frequency translate the separate bands down to a frequency range suitable for acquisition by digitizing channels. Note that for the lowest frequency band, no down-converter is employed and the signal is fed directly to the oscilloscope front-end. For the high-frequency bands, the down-converter modules have digitally controllable gain adjust and the usable band does not extend to zero frequency (DC).

Each down-converter consists of variable attenuation and gain elements, a mixer, a local oscillator (LO), image reject filters and fixed gain amplifiers. There are also mechanisms for locking the reference clock of the LO to the oscilloscope timebase and sample clock generation along with means for inserting similarly locked calibration tones into the mixer [13] radio frequency (RF) inputs in each band for LO phase calibration. These methods are used for subsequent digital LO regeneration.

Each down-converter is driven by a LO that is set higher than the edge of the frequency band. In this way, the input to the down-converter is translated down and flipped over in frequency (i.e. high-side down-conversion is employed).

On the DSP side, processing is performed to regenerate the input signal from the three 80 GS/s acquisitions. The recombination involves upsampling from 80 to 240 GS/s, digitally synthesizing a phase-locked rendition of the LO, up-converting the signal back to its original frequency band, rejecting unwanted images, and combining the results. The final result is a 100 GHz, 240 GS/s waveform acquisition [14].

## DBI in Reverse

In 2007, LeCroy patented a high-speed arbitrary waveform generator [15] based on the DBI technology. I call it *DBI in reverse*. Lately, other DBI-like methods have been proposed [16]. The basic block diagram from the patent is shown in Figure 3. Here we see a desired output waveform processed by some DSP and loaded into two memories. The memory designated as low frequency (LF) plays the low frequency

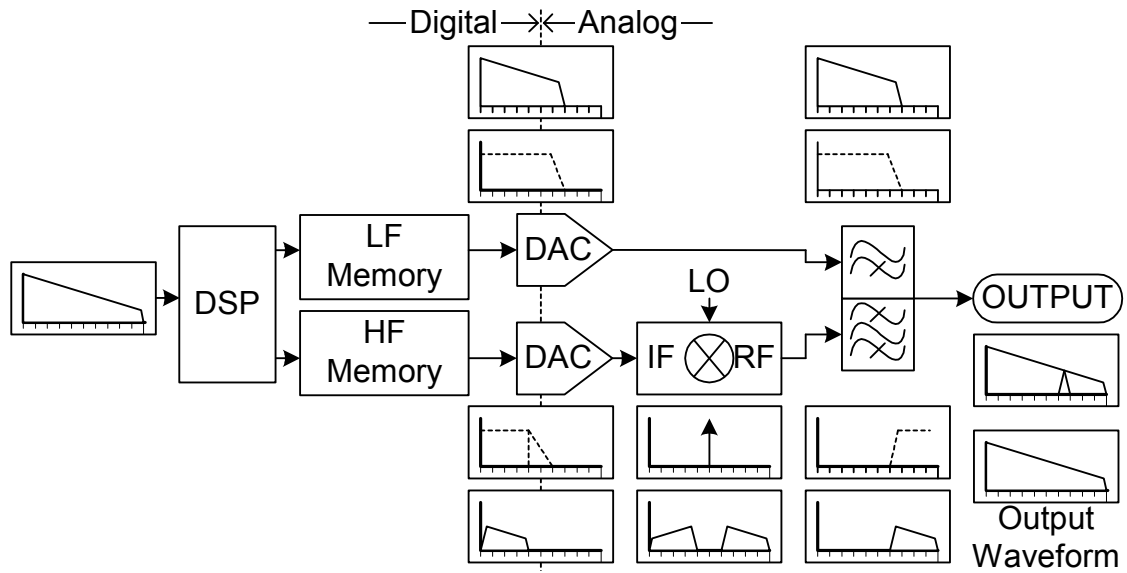


Figure 3: DBI based AWG

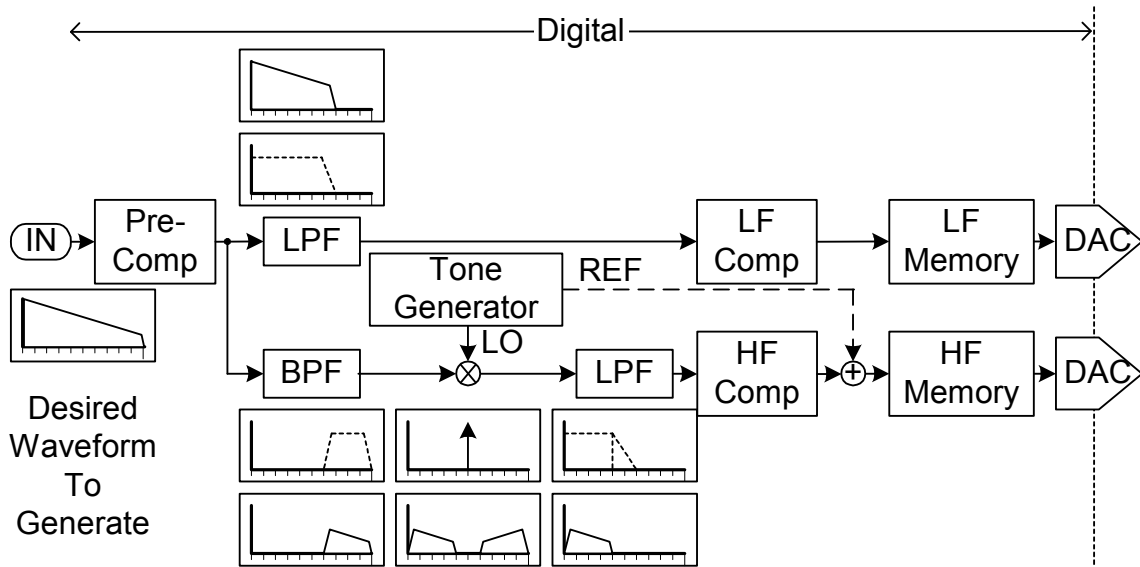


Figure 4: DBI based AWG DSP Block Diagram

portion of the signal into a digital-to-analog converter (DAC) just like in a modern AWG today. The high frequency (HF) memory contains the high frequency portion of the signal. This signal is played into another DAC. The output of this DAC enters a mixer that mixes the signal with an LO, but unlike DBI used in scopes, here the desired image is the high-frequency one. The low frequency and high frequency waveforms enter a diplexer which combines the two frequency bands that can be essentially twice the bandwidth of each individual DAC.

In this type of design, the data that goes into the memories must be significantly preprocessed. A block diagram of this preprocessing is shown in Figure 4, which implements the processing in the DSP box in Figure 3. The basic idea is to reverse the effects of the mixing and recombination. Here we see the waveform low-pass filtered to produce the LF waveform. The waveform is bandpass filtered, mixed with a digital version of the LO and low-pass filtered to produce the low frequency waveform that is stored in HF memory, but representing the high-frequency portion of the original signal.

One important thing that might not be obvious from this arrangement regards the determination of and enforcement of the LO phase in the system. In order for the two bands to combine properly, the phase of the LO used to actually mix the HF band waveform in Figure 3 must remain locked to the phase of the LO waveform used to preprocess the HF band digital waveform in Figure 4. There are many ways to do this and in a subsequent section we will discuss what was actually done for this experiment. In Figure 4 we see a reference tone inserted into the digital signal at the end of the processing chain. The LO would presumably be a multiple of this reference signal in frequency. When these types of tones, referred to as *pilot* tones are inserted, they are expected to be extracted and removed in the analog processing and used as the reference for the actual LO supplied to the mixer.

## The Bell Labs High Speed AWG

The AWG developed at Bell Labs benefited greatly from two things beyond the existence of the high speed AWG patent:

1. A division of Fujitsu that develops high speed complementary metal oxide semiconductor (CMOS) ADCs and DACs for high-speed optical communication systems developed a DAC capable of sampling at 80 GS/s with approximately 30 GHz of bandwidth and Bell Labs had access to development boards containing these DACs [17]. The importance of this is the similarity between this DACs performance and the performance of the oscilloscope channel in a LeCroy DBI DSO.
2. Because the Bell Labs engineers have such a thirst for real-time oscilloscope bandwidth, and because they work only about fifty miles south of our facility, we've developed a good relationship over the years. Because Teledyne LeCroy and Nokia Bell Labs worked together on this project, we were able to use the Fujitsu DAC and also many components in the 100 GHz Teledyne LeCroy oscilloscopes, which would require the frequency plan dictated by the DAC capabilities to match that dictated by the capabilities of one oscilloscope channel [18].

The AWG actually built during the experiment in early 2016 is shown in Figure 5 along with its block diagram provided in Figure 6. On the left is the Fujitsu OOLA board containing four DACs whose outputs are locked together. Each DAC is sampling at  $32\times$  the common reference clock supplied by an external generator. Here, we supply 2.5 GHz for a common DAC sample rate of 80 GS/s. Three of the DACs are supplying up to 36 GHz of frequency content. The LF band DAC is supplying DC-35 GHz of the

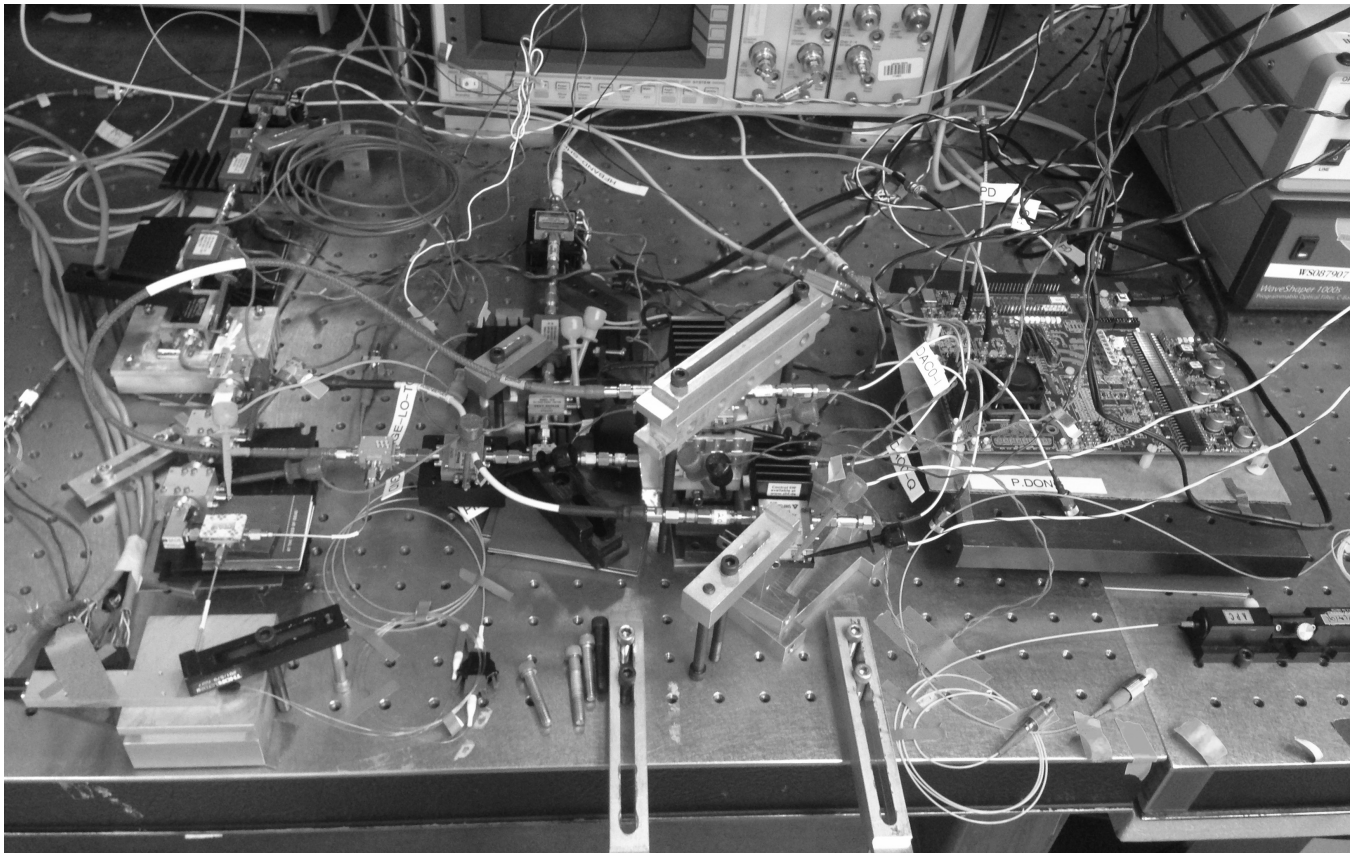


Figure 5: 100 GHz, 240 GS/s Arbitrary Waveform Generator

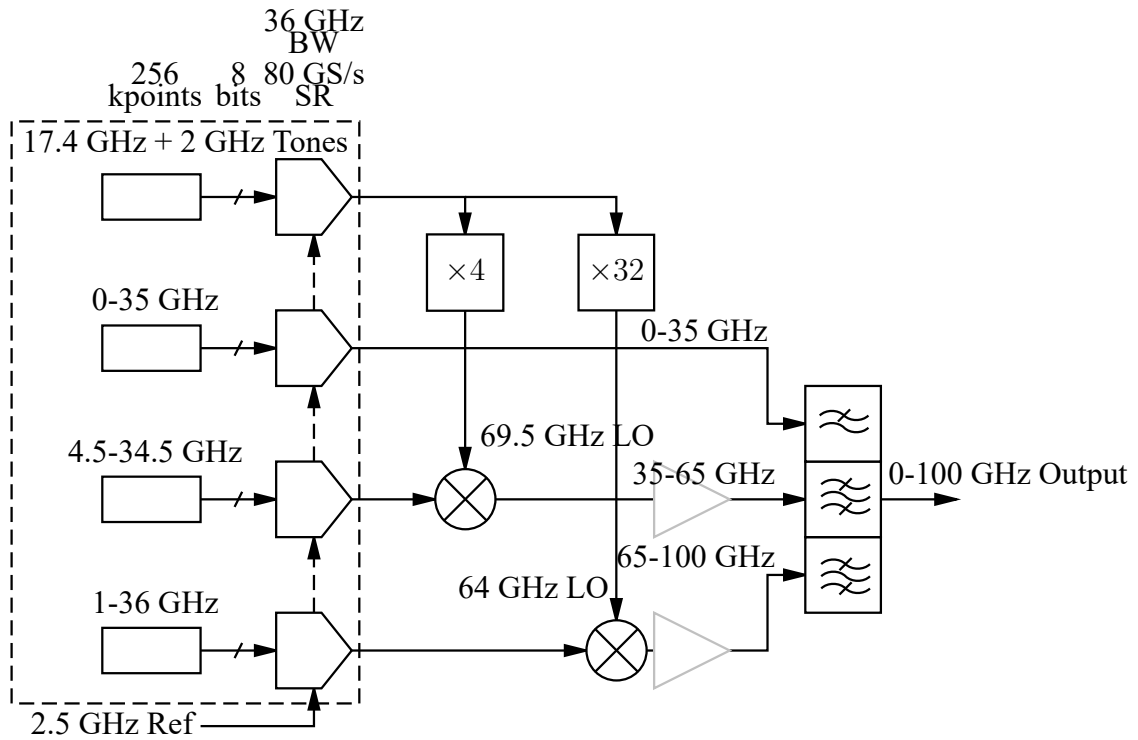


Figure 6: 100 GHz AWG Block Diagram

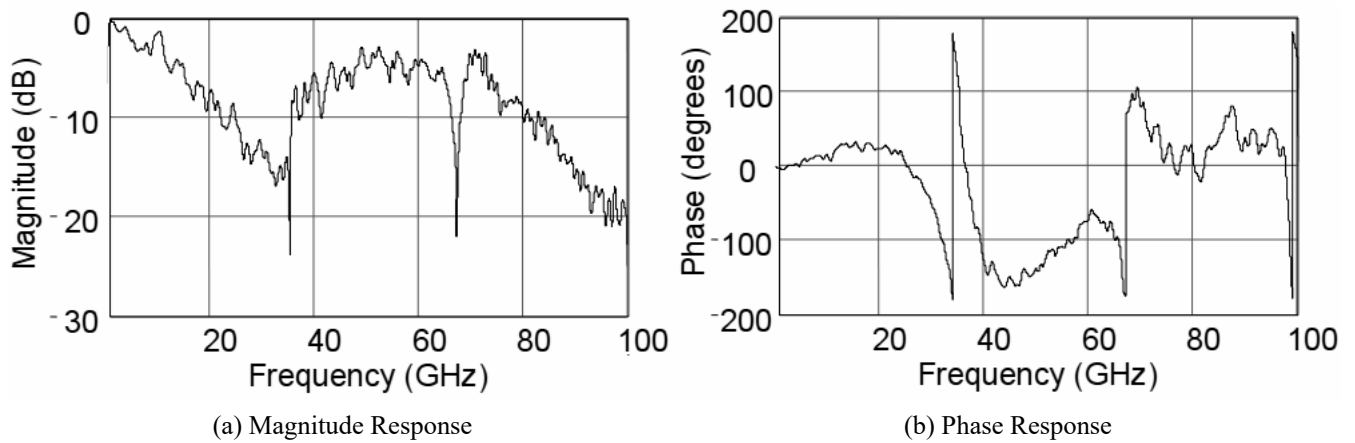


Figure 7: 100 GHz AWG Raw Response

output signal directly. The medium frequency (MF) band DAC is supplying signal between 4.5-34.5 GHz representing the output signal content of 35-65 GHz. The HF band DAC is supplying signal between 1-36 GHz representing the output signal content of 65-100 GHz.

The fourth DAC is used to supply pilot tones for the LO generation. These are two tones summed together, one at 2 GHz and the other at 17.5 GHz<sup>2</sup>. These tones were utilized based on ready availability of frequency multipliers and the chosen LO tone frequencies, which themselves were driven by whether high- or low-side up-conversion was being utilized and the already developed triplexer frequency plan. Note that if a fourth DAC were unavailable, and if we had more time, we would have utilized the unused frequency content in the MF band DAC to carry one or more pilot tones. The pilot tones are fed to two multipliers. Each multiplier has a band of frequencies that it accepts, so no filtering of the dual tones was required. The first multiplier multiplies the 17.5 GHz tone by 4 to produce a 69.5 GHz LO for the MF band mixer. The second multiplier multiplies the 2 GHz tone by 32 to produce the 64 GHz LO for the HF band mixer.

As each of the MF and HF band DAC output signals enters each mixer, frequency conversion takes place. For the MF band, two images are produced: a low image between  $69.5 - 34.5 = 35.5$  GHz and  $69.5 - 4.5 = 65$  GHz and a high image between  $69.5 + 4.5 = 74$  GHz and  $69.5 + 34.5 = 104$  GHz, the latter image being irrelevant. Because the LO is placed above the output band, this is called high-side up-conversion. This is generally preferable for signal fidelity, but this means that the frequency content loaded in the MF memory is actually reversed in frequency.

For the HF band, two images are produced: a low image between  $64 - 36 = 28$  GHz and  $64 - 1 = 63$  GHz and a high image between  $64 + 1 = 65$  GHz and  $64 + 36 = 100$  GHz, the former image being irrelevant. Because the LO is placed below the output band, this is called low-side up-conversion. This is generally not preferable for signal fidelity, but was necessitated by component availability. The frequency content loaded in the HF memory is in proper memory order. In a later experiment, the HF band was modified for high-side up-conversion through component changes.

Note that in both the MF and HF band conversions, the LO is driven with significant power at 7-8 decibels (dB) relative to 50 mW into 50 Ohms (dBm) and there is significant leakage of the high power LO to the RF mixer port; in fact the LO is the largest signal coming out of the RF mixer port. This frequency must be rejected downstream by the triplexer.

While the DACs themselves could produce outputs up to  $900 \text{ mV}_{pp}$  (3.06 dBm), the conversion loss of the mixers means that the final output signal after equalization is only  $126 \text{ mV}_{pp}$  (-14 dBm). In a later experiment, amplifiers were placed in the MF and HF bands (as indicated gray in Figure 6), bringing the output power level to  $1.2 \text{ V}_{pp}$  (5.56 dBm).

Because of the common reference clock for each DAC, the tones generated by the fourth DAC, and the multiplied tones, remain phase-locked to the DAC waveforms. Therefore the frequency band outputs of the LF DAC and the MF and HF band mixers are replicas of the portion of the signal in different bands with only a possible delay which is pre-calibrated out prior to loading the waveforms in memory. They are essentially summed by the triplexer, which is the same triplexer inside a Teledyne LeCroy LabMaster 10-100Zi [19][20].

The instrument was characterized by populating all frequency components with equal signal power across the three DAC bands which resulted in the raw spectral output of the composite signal shown in magnitude and phase in Figure 7. The individual DAC frequency roll-offs in combination with the filter

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<sup>2</sup>the DACs are limited to record lengths that are multiples of 1024 and the output tones had to repeat with no discontinuities as the waveform repeats, so the actual frequencies were 2.0001221 GHz. The 17.5 GHz tone is exact.

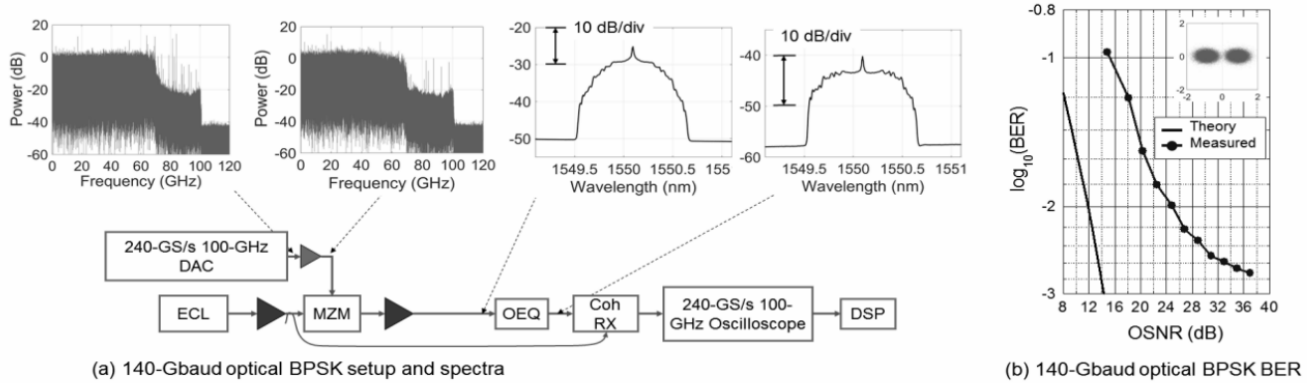


Figure 8: 140 Gbaud BPSK Optical Communications Experiment

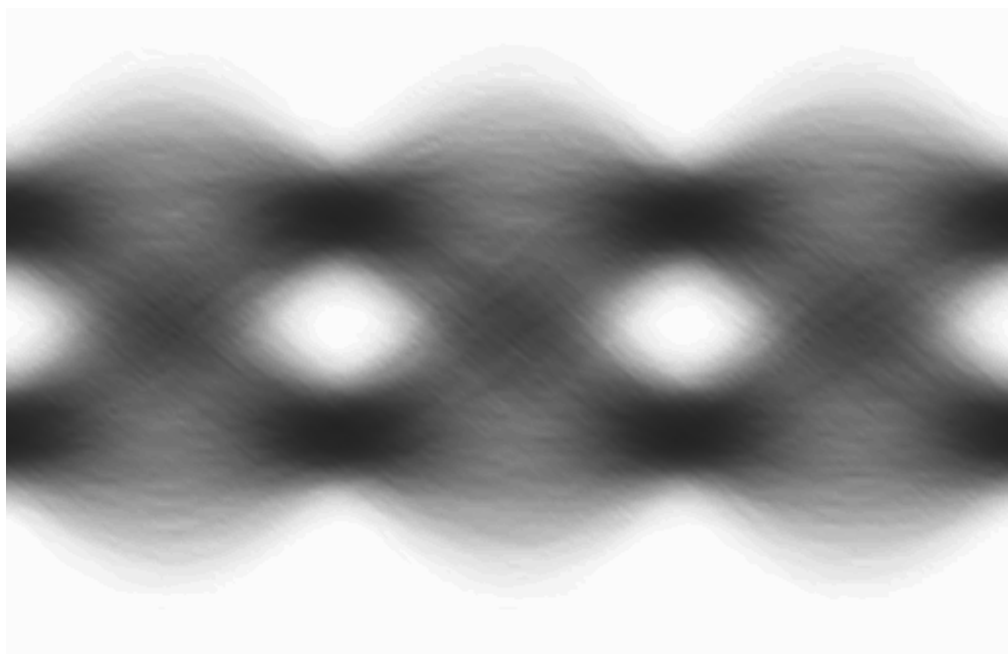
characteristics of the triplexer, especially at the filter edges, are clearly visible in 7a where an undesirable 20 dB of response variation is visible across the band. One especially sees the hard cut-off triplexer characteristics in 7b, which causes huge swings in phase at the band edges. These swings in phase are not entirely the *fault* of the diplexer and can be compensated by delay, LO phase adjustment, and crossover phase compensation.

In order to compensate for the raw response, we used digital predistortion during signal preprocessing. In other words, the desired waveform was digitally filtered with a filter having the inverse response of the channel prior to decomposition into its frequency bands. After calibration, the waveforms generated by the composite DAC represent the desired digital signal. As a first test signal, the team generated an orthogonal frequency division multiplexed (OFDM) signal covering 100 GHz of electrical bandwidth. We used OFDM with a fast Fourier transform (FFT) size of 12288, out of which 5120 subcarriers are loaded with signals covering frequencies from DC to 100 GHz. QPSK is used to modulate each OFDM subcarrier. The subcarrier frequency spacing was 19.5 MHz. As mentioned previously, the peak-to-peak voltage at the output of the triplexer is 126 mV, limited by the RF mixers used in our setup. The resulting electrical signal is directly connected to a Teledyne LeCroy LabMaster 10-100Zi 240-GS/s 100-GHz real time oscilloscope, followed by standard offline OFDM DSP [21]. The detected spectrum was analyzed from DC to 100 GHz. Phase noise was clearly visible in the two up-converted bands due to LO phase fluctuations, to be suppressed by future engineering of the LO paths. Also, there was a strong notch around 66.5 GHz that is due to imperfections in our current DBI setup at the second triplexer seam, which was not yet digitally compensated, combined with the behavior of the oscilloscope, which is also based on DBI technology and uses the exact same three frequency bands.

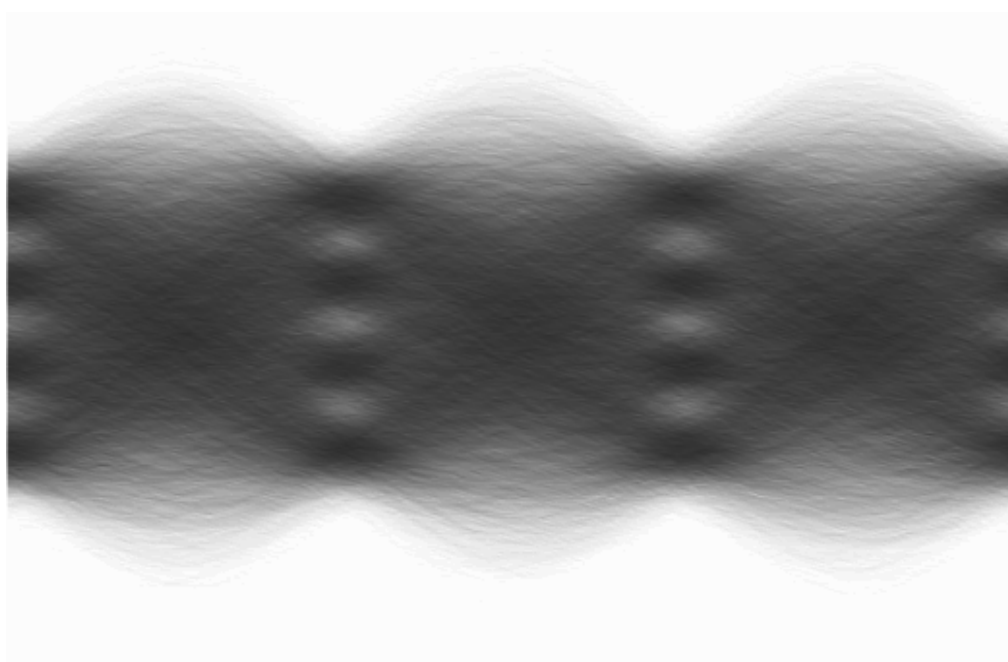
Because of the roll-off seen in the DACs, future experiments envision using an equalizer at the output of each DAC to compensate this effect.

The goal of this experiment was first and foremost optical as the intent (which was achieved) was to generate the highest bandwidth single carrier signal generated on a single polarity and wavelength. The results of this experiment are shown in Figure 8 [22, 23] where the optical components limited the optical signal bandwidth to about 70 GHz resulting in the generation of a 140 Gbaud optically generated and received signal, but to be fair, the experiment was limited by the relatively small amplitude of the output signal.

The eye diagrams from the original experiment are shown in Figure 9. In both Figure 9a and Figure 9b, the nominal amplitude is 126 mV<sub>pp</sub> and the symbol spacing is 5.263 ps. In Figure 9a we have a 190 Gb/s



(a) 190 Gb/s NRZ Signal



(b) 190 GBaud (380 Gb/s) PAM-4 Signal

Figure 9: High Speed Signal Generation

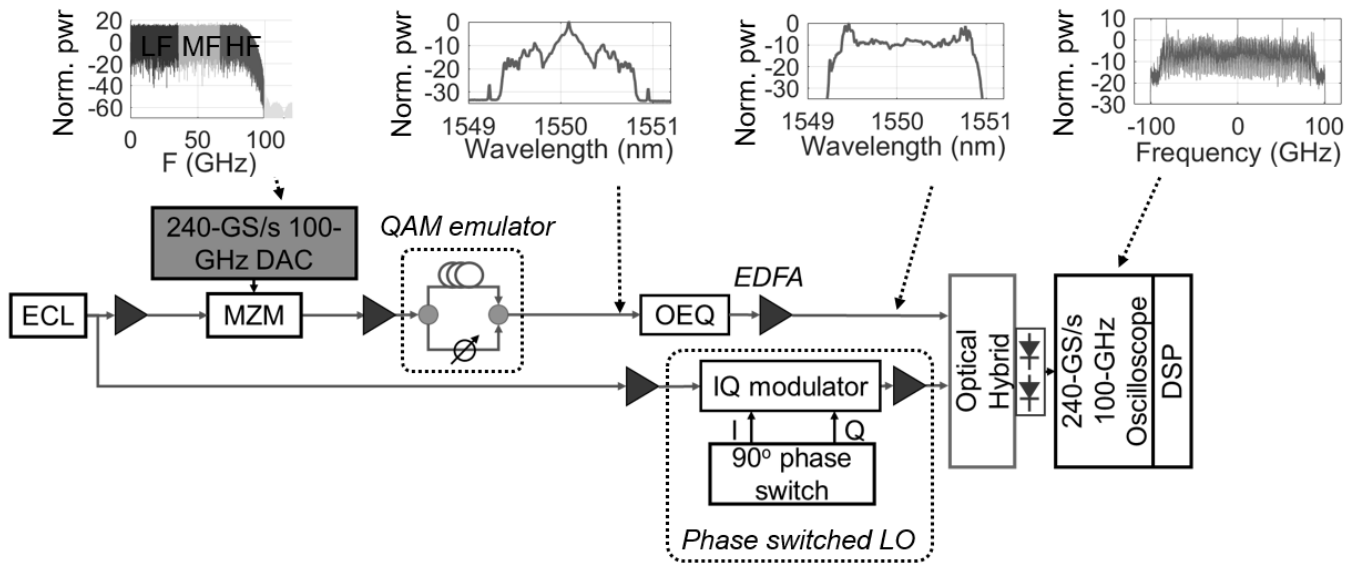
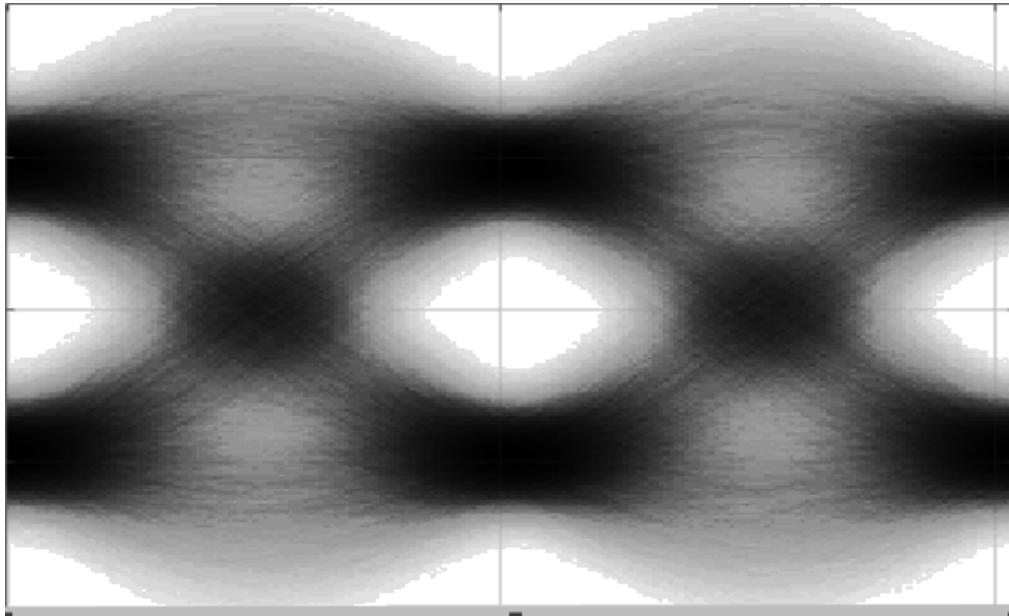


Figure 10: 180 Gbaud QPSK Optical Communications Experiment

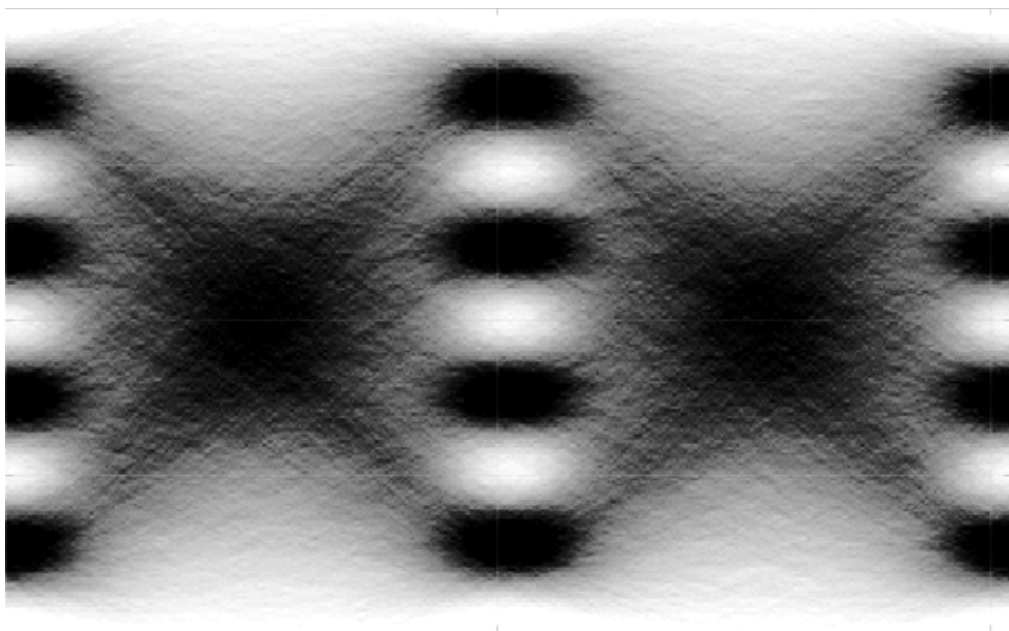
NRZ eye diagram exhibiting a reasonably large eye opening and with a measured bit error ratio (BER) of  $1.1 \cdot 10^{-4}$ . In Figure 9b we have a 190 Gbaud, four level pulse amplitude modulated (PAM) eye diagram. As indicated by the eye closure, the BER is not very good and is measured at  $3.2 \cdot 10^{-2}$ .

In the second experiment, the amplifiers enabled slightly faster signals and much higher amplitude. Also, the high-side up-conversion applied to the HF band improved the signal fidelity. The basic idea of this experiment is shown in Figure 10 and was to demonstrate the generation and coherent detection of 180-Gbaud QPSK. The single-carrier and single-polarization system achieved a line rate of 360-Gb/s [24]. Even though it was not an object of the optical communication part of the experiment, we generated electrical NRZ and PAM-4 signals at a slightly faster rate as shown in Figure 11 where the nominal symbol spacing is 5.128 ps. In Figure 11a we have a 195 Gb/s NRZ eye with a nominal peak-peak amplitude of  $1 V_{pp}$  also exhibiting a large eye opening. The BER was measured at  $3.2 \cdot 10^{-6}$ . In Figure 11b we have a 195 Gbaud, four level PAM eye diagram with a nominal peak-peak amplitude of  $1.5 V_{pp}$ . While the eye is much more open than in Figure 9b, the BER is not nearly as good as we generally expect in signals present in computer communications systems and was measured at  $1.4 \cdot 10^{-2}$ . In optical communications, it is common for forward error correction (FEC) to be employed and the 20% soft FEC threshold is at  $1.9 \cdot 10^{-2}$ . This means that as long as the noise is Gaussian, with a 20% overhead of FEC codes, all of the errors can be theoretically corrected.

This is thought to be the fastest PAM-4 signal ever generated and was transmitted about six inches directly into the input of an oscilloscope in a completely coaxial environment for acquisition and analysis.



(a) 195 Gb/s NRZ Signal



(b) 195 GBaud (390 Gb/s) PAM-4 Signal

Figure 11: High Speed Signal Generation

## Acknowledgements

None of this work can be attributed to a single person or even a single group of people. Although the final results are quite astounding, often the performance in experiments like this are based heavily on the performance of various components produced by engineers whose work remains in the background. Although we can't make an exhaustive list, we can at least try to acknowledge engineers we know of.

The authors would like to thank the design and development engineers at Teledyne LeCroy who developed the LabMaster 10-100Zi oscilloscope.

We'd also like to thank the other researchers at Nokia Bell Labs, where the collegial atmosphere leads to all sorts of collaborative contributions even when not named as an author.

The integrated circuit designers at Socionext (formerly Fujitsu) designed the OOLA DAC whose speed and performance were critical.

The engineers at Phase Matrix, a division of National Instruments designed many of the microwave components used in this experiment, specifically the triplexer. We'd like to thank specifically Irfan Ashiq and Dr. Amarpal Khanna for making an extra triplexer on very short notice, often working weekends.

Chris Marki of Marki microwave provided a sample mixer used in a later experiment when high-side up-conversion was applied to the HF band. Thanks Chris.

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