Application Note Optical Delay Line

Optical Delay Line Application Note

2021

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Glossary

ALT ODL	Altimeter Optical Delay Ling
BIT	Built-In Test
CW	Continuous Wave
dBc	Decibels
dBm	Decibel (referenced to milliwatts)
DCM	Dispersion Compensation Module
DFB	Distributed Feedback Laser
EDFA	Erbium-Doped Fiber Amplifier
EMI	Electro-Magnetic Interference
EW	Electronic Warfare
LO	Local Oscillator
MTI	Moving Target Indication
NF	Noise Figure
ODL	Optical Delay Line
OEM	Original Equipment Manufacturer
RADAR	Radio Detection and Ranging
RF	Radio Frequency
RFI	Radio Frequency interference
RIN	Relative Intensity Noise
SAW	Surface Acoustic Wave
SM Fiber	Single-Mode Fiber
SNR	Signal-to-Noise Ratio

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1. General

An optical delay lines system (ODL), incorporates high-performance lasers such as DFBs, optical modulators for high operation frequencies, photodiodes, and optionally other components such as optical dispersion compensators, optical switches, optical amplifiers, and Pre and Post RF amplifiers to provide exceptionally high performance. The ODL optical system supports very high bandwidths of analog signals, high sensitivity with a wide dynamic range for various delays. In addition, the Altimeter Emulator is also considered as an ODL type.

2. Optical Delay Line Methods

An Optical Delay Line method is the most accurate and reliable method for time-domain measurement for delay times of a few nanoseconds to hundreds of microseconds. Optical Delay line is a method of wave guide where the media is fiber with a fixed index of refraction and relative constant group delay variation. The main advantages of this method as compared to other methods are:

a) Delay Length

Delay length is the long achievable delay line due to the extremely low loss of the fiber (~0.25dB/Km), which is not achieved with any other method. There are methods that can measure a range of picoseconds, such as light reflection, but they do not cover the typical range of Radars or EW systems. There are also methods for very long delay lines in the order of milliseconds that are not accurate for practical lengths of delays. Therefore, an Optical Delay Line is the most suitable method for length range from a few nanoseconds to hundreds of microseconds. Moreover, utilizing switching or progressive system architectures, it is possible to include several different delays in the same system which saves space, weight, and budget.

b) Bandwidth

An Optical Delay Line can supports bandwidths from MHz range to a tenth of gigahertz. This enables using the ODL in various applications that require high bandwidth, where other waveguide methods are limited in allowed bandwidth and applications. For example, SAW is used for a bandwidth of a few tenths of kilohertz.

c) Group Delay Variation

One of the most important issues for Radar designers is, that the delay will be equal across the entire bandwidth. Thanks to the fiber, the group delay is constant and very small in compression to the delay length.

d) Spurious

The ODL spurious level depends on the RFoF internal links and other internal components. The challenge is to clean noise sources as much as possible.

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e) Phase Noise

An important parameter in the performance of airborne radars is the phase noise of the radar's carrier frequency. Low phase noise is important for accurate long-range detection of a target. Many phase noise test sets utilize waveguide delay lines as part of the test circuit. Because of its size, weight, and signal attenuation, a typical waveguide delay line has length limitations. Replacing the waveguide with a fiber-optic delay line allows for a major reduction in size and weight, as well as an added ability to improve the sensitivity of the test set in measuring phase noise close to the radar's carrier frequency. A laser diode with low RIN can provide at 0 delay length a phase noise less than -130 dBc (input of 0 dBm) at 10KHz separation.

3. Optical Delay Line Applications

There are various applications that can use ODL systems, including:

- Radar range calibration;
- MTI;
- Clutter Canceller;
- BIT;
- Ground-Based System Test;
- Radar Warning Receiver;
- Jammers for EW Systems;
- Timing Control;
- Path Delay Simulation; and (x) Phase Shift Discriminator.

For more information, see Section 7 below.

4. Optical Delay Line Main Features

- Supporting transmission of RF and Microwave analog signals, covering L, S, C, X, and Ku bands, for various applications.
- Supporting width bandwidth analog signals.
- Supporting various delay lines ranging from few ns up to hundreds of µsec.
- High dynamic range
- Excellent delay repeatability and phase linearity
- Small Group Delay Variation
- Easy operation – manually or remotely through RS-232 or Ethernet

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5. Optical Delay Line System General Description

The ODL is an electric-optic-electric instrument. It performs fixed time delay(s), between a few nanoseconds up to several hundred microseconds, for RF signals from 0.1 up to 40 GHz and more. There are low-frequency ODL versions of 0.1-6 GHz and high-frequency ODLs versions of 12GHz, 18GHz, 28 GHz, 30GHz, and 40GHz ODL.

The RF input signal is converted into an optical modulated signal. The optical signal is transmitted into long single-mode fiber, usually at 1.55 micron wavelength. Passing the fiber, the optical signal is converted back into an electrical RF signal. The electrical control on the ODL elected optical system is done automatically, with no need for any tuning by the operator.

The ODL is generally operated as a standalone system with no need for any intervention by the operator - it can also be controlled externally from a PC through various communication interfaces. The RF engineer can simply treat the ODL system as a "black box" which transmits the analog signal, either with narrow or very wide bandwidth, over large distances up to several tens of km with minimum losses and distortion. See Figure 1 below for an ODL basic block diagram.

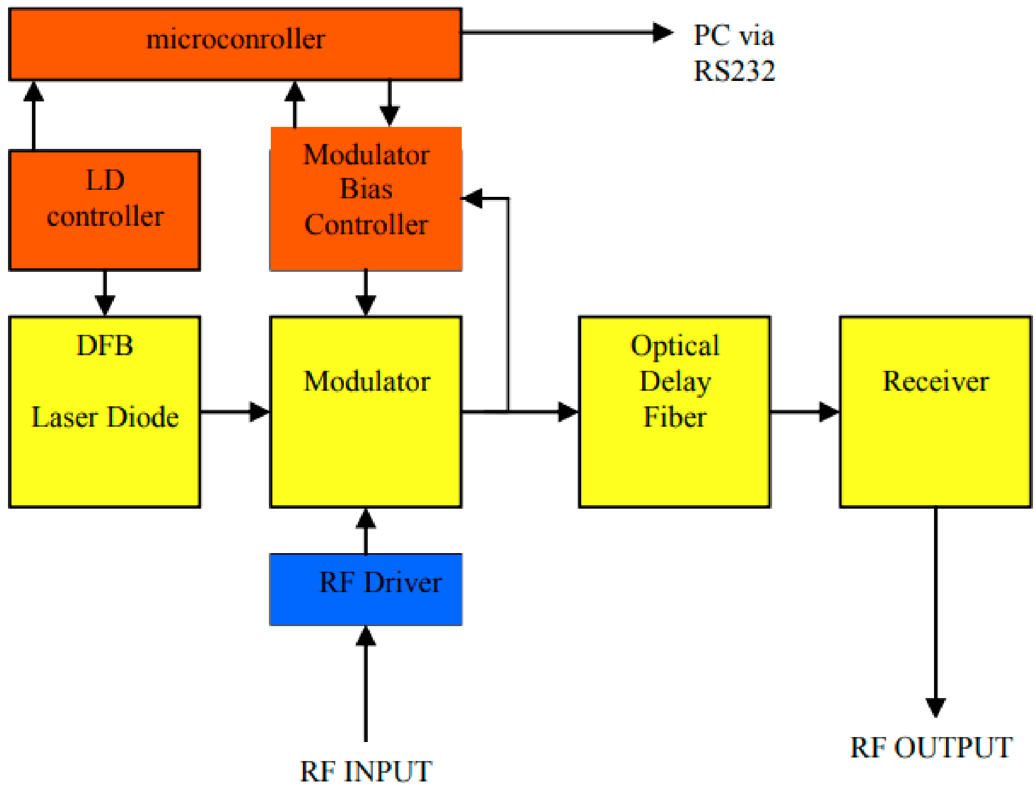

Figure 1 - ODL basic block diagram

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6. Optical Delay Line Block Diagram and main Configurations

6.1 Fixed Delay Line System

The basic ODL system configuration consists of a Transceiver and fixed Delay Line modules that are integrated in one enclosure (See Figure 2 below). ODL versions where the Transceiver and Delay Line units are separated into two modules are optional for providing the user with flexibility when using one ODL Transceiver unit with several passive Delay Line units. The ODL in one enclosure is robust since the Delay line fiber is fused to the system.

Figure 2 - ODL module

6.3 Progressive Delay Line systems

Progressive Delay Line is another approach for variable delay systems. It consists of an ODL system configuration which includes cascaded 1:2 and 2:2 optical matrixes with several different delay lines in between (replacing the two optical switch matrixes 1:8 in Figure 3). The cascaded switch is shown in Figure 4 below, where the desired combination of delay lines is defined for the desired delay. It shows four progressive delay line-cascaded switches matrixes. With such a configuration, the user can select any of the 16 combinations of possible delay values (16=24) e.g., a delay which is equivalent to Dtot= D1+D2 +D4 etc.)

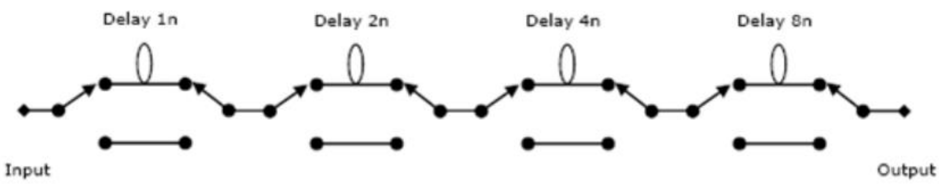

Figure 3 - Progressive Delay Configuration consisting of 4 optical switches

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7. Optical Delay Line System – Design Considerations

The Insertion Loss of a basic analog fiber optic link is in the range of 30 dB (in RF domain), depending on (i) the quantum efficiency of the laser and (ii) photodiode, and on the (iii) laser to fiber coupling efficiency. It is noted that 1 dB optical loss is equivalent to 2 dB system loss in the RF domain. Typical fiber loss at 1.55 mm wavelength is in the order of 0.25 dB/km, so for example, a 300 sec long delay line (~90 km delay ~ 62 km fiber), the fiber optical loss will be about 15.5 dB, i.e. RF loss of 31 dB.

For such long optical delay lines, adding an optical amplifier (EDFA) can compensate for the entire fiber loss and, in parallel, considerably reduce the system noise figure (NF). Figure 6 below shows S21 (ODL system Gain and Gain Flatness) for a typical ODL system. This characteristic response is independent of delay time as long as no dispersion effect takes place.

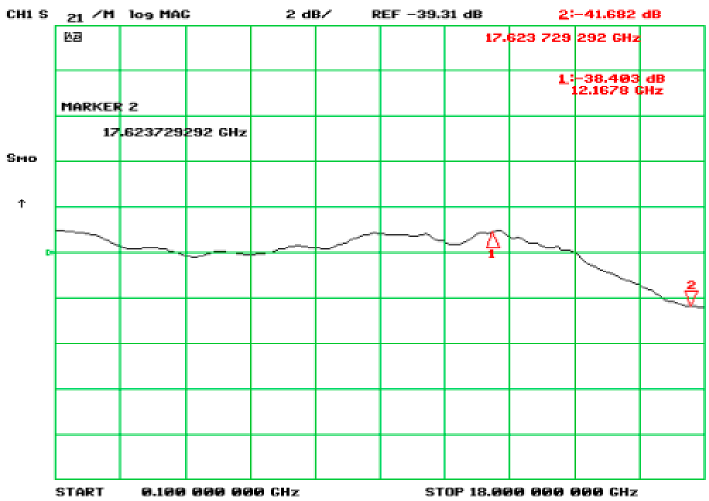

Figure 4 - System Gain (S21) of a 10 µsec delay ODL system, up to 18 GHz operation frequency

a) **Optical Dispersion of long fibers at high RF frequencies** causes additional insertion loss at the specific frequency range per defined delay line length(s), where the insertion loss deep can reach 20 dB and more. The optical dispersion loss can be eliminated by using an Optical Dispersion unit connected to the long delay line for compensating the undesired dispersion loss (see Figure 6). The 'deep' around 15GHz is due to the ~20.7 km SM fiber dispersion effect at 1.55 mm wavelength. The dispersion effect can be eliminated by adding a DCM unit with negative dispersion.

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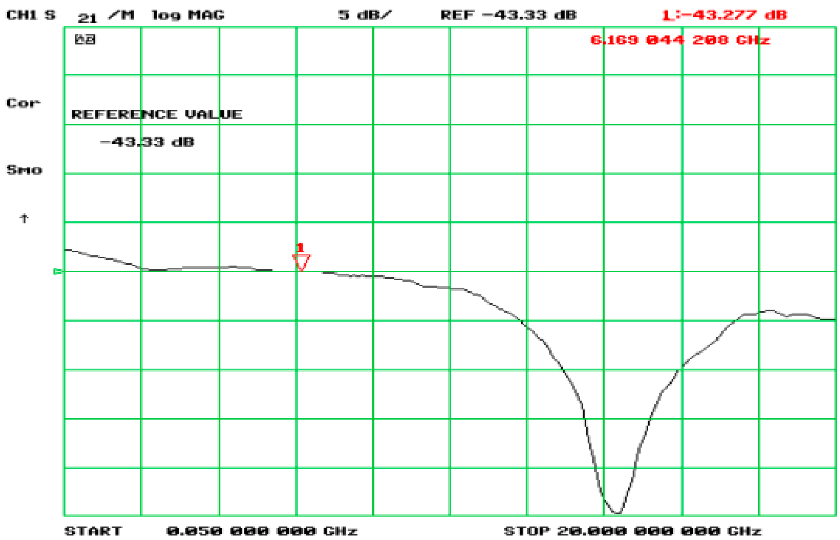

Figure 5 - System Gain (S21) of a 100 µsec delay ODL system up to 20 GHz

Here we should write about the method to select DCF:

b) The **basic ODL system configuration** consists of one Transceiver and one fixed Delay Line module that are integrated in one enclosure configuration. Depending on the length of the delay, such an ODL is typically packaged in 2U enclosure (short delay) or in 3Uenclosure in case of long delays (e.g., > 50 µsec). Mini ODL enclosures are optional, depending on the required ODL configuration and specifications.

Other ODL versions where the Transceiver and Delay Line unit(s) are separated into two (or more) modules are optional. Due to the flexibility and immunity of the RFI and EMI properties of optical fibers, ODL systems could be built with the delay spool removed from the Transceiver. In such a case, the Transceiver unit (including optical switches if required) is connected to the Delay lines through SM short fibers connecting the ODL optical input and output ports to the passive Delay units.

c) **Phase Noise**: ODL Phase noise is smaller than -130 dB/Hz at 10Khz from the carrier for various operating frequencies and delay lines. Typical phase noise is shown in Figure 7 below. The measurement is limited by the Measuring Equipment noise: PN<-127 dB at 1 MHz from the carrier, PN <-113 dB at 100 KHz from the carrier, and PN<-105 dB at 10 KHz from the carrier.

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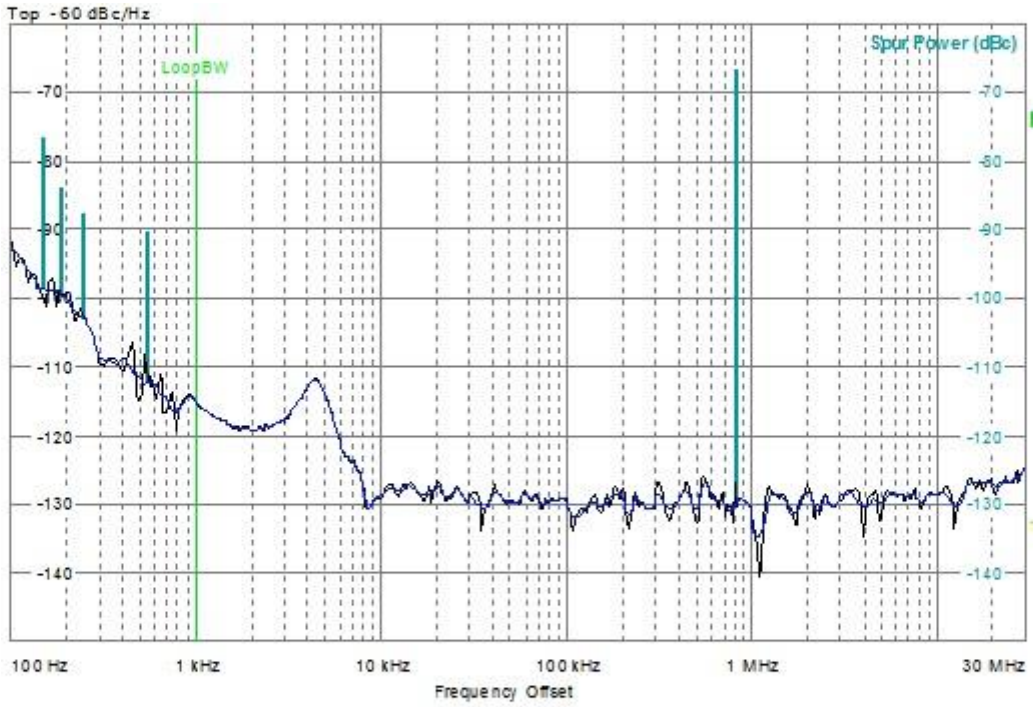

Figure 6- ODL Phase Noise measurement at 10GHz

d) **RF Amplifiers considerations**: Pre and/or Post RF amplifiers can compensate for ODL Insertion Loss and for the optical loss in case of long delay lines that is translated into RF loss in the ODL's photo-detector unit. The advantage of using Pre-Amp is, that it also improves the system Noise Figure and the SNR. On the other hand, it reduces the Input P1dB (typically less important for most of the ODL applications). Alternatively, adding a Post Amp will improve the ODL system gain and will not affect the system Input P1dB, but will not improve the system Noise Figure. Adding RF amplifiers will increase the ODL system Gain Flatness, where in case of requirement for better Flatness, either EDFA could be used instead (in case of long delay lines), or RF amps with special low gain flatness can be selected.

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e) **Environmental and Reliability**: The basic optical transceiver units, including DFB laser, optical modulator, photodiode, optical switches, EDFA, and Optical Dispersion compensator as applicable, are all packages in rugged packages and capable of withstanding considerable shock and vibration without damage.

8. Optical Delay Line System – Main Applications

a) Moving Target Indication and the clutter canceller are basically the same. In this application, each received echo pulse is subtracted from the previous echo, which has been stored in the delay line. Any component of the signal that has not changed will thus be subtracted from itself to give a zero output. This could be ground clutter or a stationary target. A moving target will generally have an amplitude change as well as a Doppler frequency shift. The difference between successive pulses in this case, will result in a dc or low-frequency output proportional to the frequency (phase) shift (speed information) and the change in amplitude. Typical delay time in this application ranges from several hundred nanoseconds to several microseconds.

b) Another application uses the delay line as BIT equipment for Radar systems. Radar systems generally have some dead time between the last echo received and the next transmitted pulse. Some self-testing is accomplished during this time (noise performance, dc tests, etc.). In addition, the system may periodically break its operational cycle to perform self-testing with a simulated echo. The same kind of testing is also performed during regular manufacturing and as part of regular testing on the ground. Such testing may involve a single fixed delay or a set of various delays which is interchanged manually. Delays for this kind of testing can vary from a few nsec to 100 µsec.

c) In the Radar Warning Receivers, the echo is received at the IFM preprocessor which identifies the frequency and sets up the local oscillator so that the signal is down converted to the IF of the signal post processor. The delay holds the signal long enough to allow the IFM to tune the LO.

d) For EW systems, there is a major interest in the fiber ODL for jamming applications. Some of these applications involve receiving, processing, and retransmitting radar pulses as false echoes with misleading information regarding the target size, speed, and direction.

e) Another application is for Multiple Antennas at the input of one receiver. In such a case, the progressively longer delays hold the signals from a number of antennas. The signals are then time-multiplexed and can be combined for processing at the same receiver. The Delays used here can be from 100 nsec range to tens of µsec. In a similar setup, the delay lines could also be used to direct the beam pattern from a number of antennas. Such a system would then be a synthetic aperture or phased array antenna.

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f) A Phase Shift Discriminator can be used as an FM demodulator and as an element in a phase noise measurement system. If the input signal is a CW signal, then the output is proportional to the difference in the phase of the signal compared to the delay time. The longer the delay, the slower the variations that are being detected. This means that long delays allow measurement of “close in” phase noise. This requires that the phase noise introduced by the delay is less than the noise to be measured.

g) The high-frequency Altimeter Optical Delay Line (ALT ODL) provides a high-performance solution for testing and calibration of radar altimeter systems. It is a compact solution, which provides superb signal performance and altitude simulation accuracy with an ultra-silent operation. It can be configured to emulate a single altitude or up to 4,096 altitude steps. The control and monitoring are done using a front panel, a navigation switch, and an LCD display, or via a USB connection. The Altimeter ODL offers very high accuracy up to 0.3ns for altitude steps under 6ft and > 0.1% above. The maximum altitude can reach 100,000 feet or 30Km in one enclosure. One of the main applications of ODL is measuring the height from the ground.

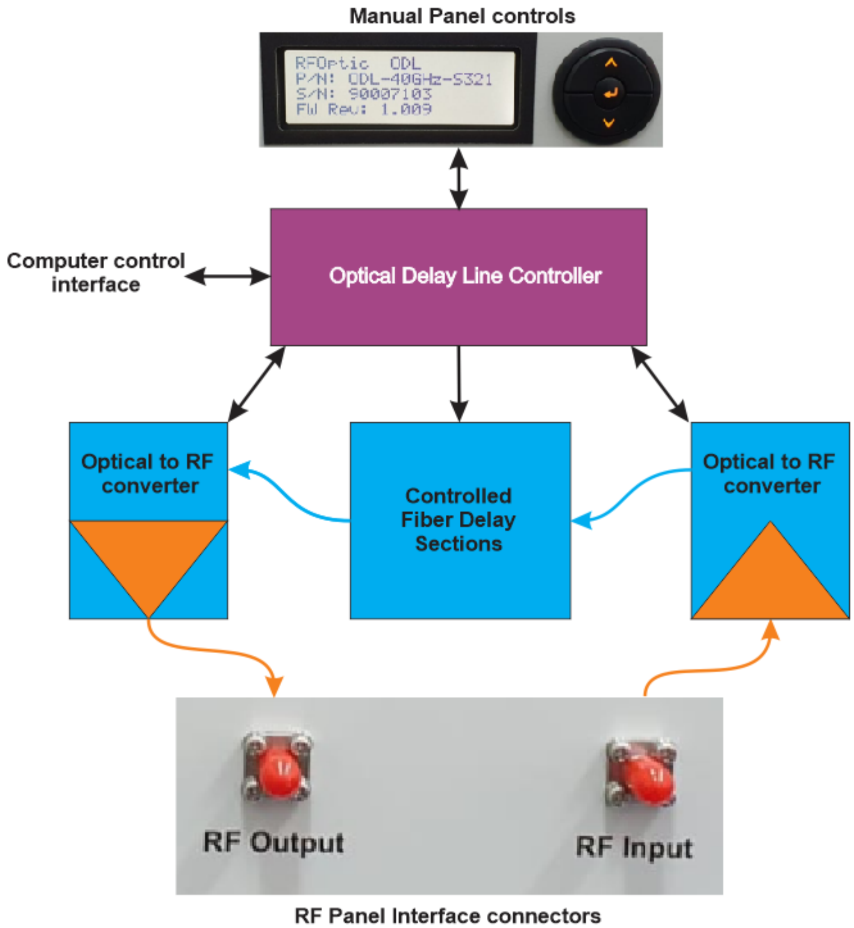

Figure 7- ODL Phase Noise measurement at 10GHz

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9. About RFOptic

RFOptic is a leading provider of RF over Fiber (RFoF) and Optical Delay Line (ODL) solutions. For the last 20 years, its team of industry veterans has been developing, designing, and integrating superior quality technology for a wide range of RFoF and ODL solutions. The solutions are deployed in various industries, including broadcasting, aviation, automotive, and defense. RFOptic offers its customers and OEMs various off-the-shelf products, as well as custom-made solutions optimized for a wide range of RFoF products at affordable prices and with a quick turnaround. RFOptic makes it its mission to help its customers to turn innovation into real business by providing them with the highest quality, cutting edge RFoF solutions as well as customized solutions based on individual requests and objectives.

For more information, please visit **www.rfoptic.com**

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