Feasibility analysis of WDM links for radar applications

D. MEENA a,b,* , FREDY FRANCIS c , K.T. SARATH c , E. DIPIN c , T. SRINIVAS a

a Applied Photonics Lab, ECE Department, Indian Institute of Science (IISc), Bangalore, India
b Electronics and Radar Development Establishment (LRDE), DRDO (Ministry of Defence), Bangalore, India
c Model Engineering College, Thrikkakara, Cochin, India

Received 9 May 2014; revised 27 August 2014; accepted 10 September 2014
Available online 26 November 2014

Abstract

Active phased array antennas enhances the performance of modern radars by using multiple low power transmit/receive modules in place of a high power transmitter in conventional radars. Fully distributed phased array radars demand the distribution of various signals in radio frequency (RF) and digital domain for real time operation. This is normally achieved through complex and bulky distribution networks. In this work, we intend to tap the inherent advantages of fiber links with wavelength division multiplexed (WDM) technology and a feasibility study to adapt these links for radar applications is carried out. This is done by analysing various parameters like amplitude, delay, frequency and phase variation response of various radar waveforms over WDM links. This also includes performance evaluation of non-linear frequency modulation (NLFM) signals, known for better signal to noise ratio (SNR) to specific side lobe levels. NLFM waveforms are further analysed using pulse compression (PC) technique. Link evaluation is also carried out using a standard simulation environment and is then experimentally verified with other waveforms like RF continuous wave (CW), pulsed RF and digital signals. Synchronization signals are generated from this variable duty cycle digital signals during real time radar operation. During evaluation of digital signals, variable transient effects for different duty cycles are observed from an amplifier configuration. A suppression method is proposed to eliminate this transient effects. Further, the link delay response is investigated using different lengths of fiber spools. It can be inferred from the experimental results that WDM links are capable of handling various signals significant to radar applications.

Keywords: WDM; Radar; RF over fiber; EDFA transient; Delay; CW; Pulsed CW; NLFM

1. Introduction

Conventional radar signal distribution networks are designed with coaxial cable or space-feeds, which make the system bulky, complex, massive and inflexible [1,2]. The inherent advantages of optical link is reduced size, weight and loss, low attenuation, immunity to electro-magnetic interference (EMI), and high bandwidth capacity [3]. Along with the advancements in microwave photonic device technology, the possibility for distribution of signals in optical domain had been opened up.

During 1980s, the components capable of working in the microwave domain emerged. Pan [2] describes an optical link capable of working at 5 GHz. By 1984, a Ti:LiNbO3 Mach-Zehnder interferometer type external modulator capable of working at 17-GHz was developed to work in 830 nm [4]. In 1987, Stephens et al. [5] described a complete radio over fiber (RoF) link while comparing the performances of direct modulation and external modulation using loss, SNR (signal to noise ratio), linearity, etc., as the parameters for 4.1—4.7 GHz and 2.0—12.0 GHz. In 1988, the applications of radar X-band signal in fiber optic links were studied by a team in Malibu [6]. They were primarily interested in providing RF delay using fiber optic link for application in radar phase noise test set and...
radar repeater test. Link characterisation was also done for AM and FM modulations in direct and external modulations using 1300 nm InGaAs laser. Cox et al. [7] described an analytical lumped-element small-signal model of directly and externally modulated analog fiber optic link. The designed link was described to be superior to others in providing a maximum bandwidth of 22 MHz for externally modulated link (11 dB transducer gain, 6 dB noise figure) and 1 GHz bandwidth for directly modulated link (−14 dB transducer gain, 33 dB noise margin). They theoretically proved that the efficiency of externally modulated Mach-Zehnder modulator (MZM) operated at moderate bandwidth with high optical power is several times higher than that of direct modulation. Due to the versatility and practicality of optical links, soon results were available in introducing true time delays in phased array antennas [8]. The paper also provides a method to overcome beam squinting and describes the use of fiber delay loops in introducing a phase delay in microwave regime, which is expected to have a great impact on phased array antenna construction. It is only a matter of time that the optical system finds its way into the avionics industry, where light weight and immunity to EMI are highly desirable. Slavenski et al. [9] discussed the transmission of analog AM and FM signals over a WDM link along with FSK digital modulated signal between antennas and on-board avionic equipment. The results were promising with insertion loss of −55 dB, carrier to noise ratio (CNR) and SNR of more than 40 dB, total harmonic distortion (THD) of less than 7% and BER of more than 1.85e-07. This proves that the link works as efficiently as coaxial cable in antenna-cockpit link with the additional benefits of WDM optical systems.

In 2007, the researchers at Thales reported about the feasibility study of using RF photonics for radar applications [1], which proved that the commercial optical components are matured enough to carry radar signals. They tested the link with local oscillator (LO) and pulsed RF signals and, they designed the direct modulated narrow band and wide band links using active and reactive matching networks. In this work they brought the results for direct modulated and external modulated link performance in terms of frequency response, noise spectral density curve vs RF frequency curve. They used CWDM (coarse WDM) optical link as part of a demonstrator architecture. The experiments prove without doubt that the optical components have matured enough to be used in military.

Ballal et al. performed a comparative study of analog and digital RoF links in terms of their merits and demerits [10]. They mentioned that various disadvantages, such as nonlinearity and chromatic dispersion, of analog RoF link can be mitigated by use of digital RoF link. Bit error rate (BER) and SNR for various input schemes, such as BPSK, QPSK and 16 QAM, were analysed for analog and digital links, and their comparison was presented. Digital RoF link shows improved performance in terms of BER parameters.

More studies followed as in Ref. [11], which characterized a direct modulated optical link for X-Band chirp modulated radar signal. Further, the link was inserted within Salex-Galileo LPI radar and the results were obtained without any performance degradation. Yao [12] described the possibility of RoF distribution along with photonic true time delay beam forming. Ghelfi et al. [13] proposed a fully photonics-based coherent radar, exploring usage of optical components to the maximum extent, rather than using photonic components only for distribution of signals. This is achieved by generating of stable radio frequency signals having arbitrary waveforms and detecting the signals by direct digitization without down-conversion. Xu et al. [14] described about the advantage of using photonic techniques to generate and distribute the microwave signals and also addressed various challenges in system realization.

In this paper, we bring out other measurement results with RF signals in terms of amplitude, delay, frequency and phase variations occurring in WDM links. As the phased array antenna has a large number of transmit/receive modules, a splitter with large splitting ratio is used to distribute the signals. To compensate for this splitter loss, an optical amplifier is required in the WDM link configuration. Modern multifunction radar uses variable duty cycle signals for its normal mode of operation. We also analyse the effects of digital signals in amplifier based WDM links and observed the transient effects with variable duty cycle digital signals. We also discuss a transient suppression method for the transmission of variable duty cycle digital signals over fiber links. During experimental evaluation, the different signals significant to radar, such as CW, pulsed CW and NLFM waveforms, are fed through the WDM link. The measurements are repeated by using different fiber spool lengths to measure signal delay, which tallies with the mathematically computed signal delay value. Even though the experiments are carried out for measurement of various parameters, we mainly focus on amplitude and delay variations within the scope of this paper. But some of the measurement results, such as frequency vs. time and phase vs. time plots, are considered to ensure the link adaptability to different waveforms.

2. Experiment

In a radar system, the echo signals are converted to intermediate frequency (IF) signals during receive operation. This down conversion process requires different local oscillator (LO) signals at each receiver module. Additionally, active phased array requires the distribution of digital signals of a bit-rate <1 M bit/s for control and monitoring purpose. A phase reference signal, having a stringent inter-element phase error requirement, is also presented to ensure synchronous operation among multiple transmit/receive modules.

Fig. 1 shows an experimental setup. RF signal is externally modulated using a CW laser operating at 1550 nm and Mach-Zehnder modulator (MZM), while the digital signal is directly modulated using a DFB laser.

The digital signals in differential format are normally used in a radar system to reduce the common mode noise occurring in the transmission line. Therefore, in order to test this kind of signal, a single ended digital signal is first converted to differential signal format using a RS422 transmitter module. A differential optical transmitter module then directly modulates
a DFB laser to produce the modulated optical output. These signals are then multiplexed using a 2:1 arrayed waveguide grating (AWG) type multiplexer. Finally at the receiver stage, the signals are demultiplexed and retrieved using respective detector modules. The different parameters associated with WDM link are listed in Table 1.

Fig. 2 shows an experimental set-up. A radar transmitter operating in 2–4 GHz is used as the RF signal source. A digital signal similar to synchronization signal in a real time radar system is generated using the digital signal source. The spectra of different waveforms are observed using a real time spectrum analyser (RTSA). This configuration helped in measuring the attenuation values associated with transmission of RF signals over a WDM link. The delay occurring in the link was measured using a digital storage oscilloscope (DSO). The experiment was repeated using different kinds of radar waveforms like continuous wave (CW), pulsed continuous wave and NLFM waveforms. Other RTSA plots used for the measurement include normal spectral plot, digital phosphor technology (DPX) [15] waveforms, amplitude vs. time (envelope) plot, frequency vs. time plot, and phase vs. time plot.

3. Results

A RF signal with a frequency of 3.1 GHz and amplitude –12.43 dBm is used as the source signal in WDM link for measuring CW-RF waveform parameters. Figs. 3 and 4 show the waveform spectra for a continuous wave input and output signals, respectively. It can be observed from Fig. 3 that the input spectra is reproduced at the receiver end, retaining the critical central frequency and bandwidth criteria. As the critical waveform parameters are retained at the receiver end, we now focus on other parameters like amplitude, delay, frequency and phase for further analysis. A few of the experiment results are included in the following sections.

Figs. 5 and 6 show the DPX waveforms of pulsed continuous wave signal at link input and output. Again output signal is observed with a constant attenuation of 27.52 dB without significant distortion.

Table 2 summarizes the measured results of different test cases. It should be noted that the link incurred a net loss of approximately 27 dB, which is independent of waveforms.

It can be observed that both the optical signals (at 1310 and 1550 nm) were continuously present throughout the experiment, confirming that there is no crosstalk between the signals in WDM FOL [9]. The measurement results of an intensity modulation-direct detection, linearly frequency-modulated (LFM) signal and X-band radar signal over a single analog link were discussed in Ref. [11]. But this paper deals with an

Table 1

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wavelength/nm</td>
<td>1550 (RF), 1510 (digital)</td>
</tr>
<tr>
<td>2</td>
<td>Fiber type</td>
<td>Single mode</td>
</tr>
<tr>
<td>3</td>
<td>RF connector</td>
<td>SMA, female</td>
</tr>
<tr>
<td>4</td>
<td>Optical connector</td>
<td>FC/APC</td>
</tr>
<tr>
<td>5</td>
<td>Laser power output/dBm</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>Photodiode</td>
<td>PIN</td>
</tr>
<tr>
<td>7</td>
<td>RoF Tx/Rx- wavelength range/nm (laser)</td>
<td>1530–1565</td>
</tr>
<tr>
<td>8</td>
<td>RoF Tx/Rx- frequency range (RF)</td>
<td>50 MHz to 18 GHz</td>
</tr>
<tr>
<td>9</td>
<td>Length of fiber spool/m</td>
<td>150, 500, 1000</td>
</tr>
</tbody>
</table>
externally modulated WDM link using other waveforms like CW, pulsed CW and NLFM radar signals.

After the evaluation of amplitude variation with various radar waveforms, the link is evaluated further for other parameters like phase, frequency and delay. Fig. 7 shows the phase variation of continuous signal (3.1 GHz) at link output with respect to time. It can be observed that the linear phase relation is maintained while the signal is transmitted through the link.

NLFM waveforms are used in modern radars owing to their improved security and better side lobe reduction [16].

Fig. 8 shows output NLFM waveform. It can be seen that the envelope is faithfully reproduced.

Figs. 9 and 10 show the frequency vs. time of NLFM input and output signals. The variation in frequency with respect to time can be observed to be nonlinear, and controlled by the non-linear coefficients used in the generation of waveform. Non-linear frequency variation of the input can be seen to be faithfully reproduced at the link output. But spectrum output alone cannot represent the side lobe level requirements. Therefore a pulse compression (PC) technique is performed on the captured samples I and Q (using RTSA) of WDM output signal.

3.1. Pulse compression of NLFM waveform

During measurement of NLFM waveform, the real time samples I and Q (in phase, quadrature) of output signal are captured using RTSA and processed with necessary NLFM coefficients to obtain a pulse compressed output of both the WDM input and the output signals. Figs. 11 and 12 show the pulse compressed results (red (in the web version)) of input and output signals along with corresponding envelope of NLFM signals (green (in the web version)). Figs. 11 and 12 show the expanded view of a single output pulse, whereas the actual transmit signal is a burst of a specific number of continuous pulses. A particular radar application requires a side lobe level of approximately 20 dB to attain a certain level of radar performance. But the resultant output signal side lobe level is approximately 25 dB (Fig. 12), satisfying the required performance level.

3.2. Simulation results

The amplitude variation for the same WDM link model is evaluated in a standard simulation environment (OptiSystem) to substantiate the experimental results (Fig. 13). A RF signal in GHz range and a digital signal in MHz range are used as input signals for evaluation purpose. The RF signal is externally modulated using a Mach-Zehnder modulator. Since OptiSystem does not support complex waveforms like NLFM, LFM, etc., a mathematical model of Mach-Zehnder modulator, which supports the generation and modulation of signals with various controlling parameters, was developed in MATLAB.

<table>
<thead>
<tr>
<th>Signal type</th>
<th>WDM RF I/P/dBm</th>
<th>WDM RF O/P/dBm</th>
<th>Link loss/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>−12.43</td>
<td>−39.6</td>
<td>27.17</td>
</tr>
<tr>
<td>NLFM</td>
<td>−11.83</td>
<td>−39.58</td>
<td>27.75</td>
</tr>
<tr>
<td>Pulsed</td>
<td>−12.1</td>
<td>−39.62</td>
<td>27.52</td>
</tr>
<tr>
<td>Measured values with waveform spectrum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>−12.57</td>
<td>−39.83</td>
<td>27.26</td>
</tr>
<tr>
<td>NLFM</td>
<td>−32.06</td>
<td>−59.x66</td>
<td>27.6</td>
</tr>
<tr>
<td>Pulsed</td>
<td>−18.73</td>
<td>−46.32</td>
<td>27.59</td>
</tr>
<tr>
<td>Measured values with amplitude vs. time plots (envelope)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>−12.41</td>
<td>−39.26</td>
<td>26.85</td>
</tr>
<tr>
<td>NLFM</td>
<td>−10.99</td>
<td>−38.83</td>
<td>27.84</td>
</tr>
<tr>
<td>Pulsed</td>
<td>−11.01</td>
<td>−38.47</td>
<td>27.46</td>
</tr>
</tbody>
</table>
This model is used as a co-simulation component in Opti-System environment along with other components for link evaluation. The modulation part of the same component is used for evaluation of CW RF signal. The obtained results show a link loss of ~27 dB, tallying with the experimental results (refer Table 3) for input of -12.182 dBm and output of -39.479 dBm.

3.3. Delay measurement for WDM link

During the measurement of delay, a pulsed RF signal, (pulse width of 1 ms and period of 10 ms) is divided into two by using a 2-way power divider and given simultaneously to DSO and WDM input. The WDM output is fed to another DSO channel. The cables used were calibrated prior to experiment.

Figs. 14 and 15 show the DSO outputs for 500 m and 1000 m long optical fiber links, respectively. The pulses are delayed by 2.56 and 5 ms for 500 m and 1000 m long links, respectively.
4. Discussion on results

4.1. Amplitude measurement

From Table 2, it is evident that, for the different kinds of RF signals, the WDM link introduced an attenuation of approximately 27 dB, which can be attributed to the losses at various components, as given in Table 4. This parameter is very important due to the fact that any variation in signal parameters of the output signal affect the performance of the radar when WDM links are used as a part of the distribution networks. Since this attenuation value is deterministic, it can be compensated either by RF or optical amplifiers as per the requirements.

The total loss of 27 dB observed with analog WDM links is found to be in consistence with the results in Ref. [7]. Even though the direct modulation is cheaper, simpler and offers a higher conversion efficiency, it can cause frequency modulation at its optical output due to the modulation of refractive index of laser cavity by the modulating signal. This spurious frequency modulation distorts the frequency modulation of the signal [1,11]. The measured results shows that the externally

<table>
<thead>
<tr>
<th>RF I/P/dBm</th>
<th>RF O/P/dBm</th>
<th>Link loss/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.43</td>
<td>39.60</td>
<td>27.17</td>
</tr>
<tr>
<td>12.182</td>
<td>39.479</td>
<td>27.279</td>
</tr>
</tbody>
</table>

Fig. 13. WDM co-simulation model in standard optical simulation software environment.

Fig. 14. Delay of pulsed RF signal with fiber length of 500 m.
modulated analog links are free from these distortions, as also shown for FM and AM analog links [9] with external modulation.

4.2. Delay measurement

The delay incurred in an optical link is primary attributed to the refractive index and length of fiber. Component propagation delays are small and hence neglected. A single mode fiber with an effective refractive index of 1.5 and carrying a 1550 nm optical signal is used for measurement. The expected delay is

\[ \Delta T = \frac{1}{v} \]

where \( l \) is the length of fiber; \( v = c/n \) is the speed of light in optical fiber; \( c \) is the speed of light in vacuum \( (3 \times 10^8 \text{ m/s}) \); and \( n \) is the effective refractive index of optical fiber. Therefore,

1) Theoretical delay for 500 m long fiber is around 2.5 ms.
2) Theoretical delay for 1000 m long fiber is around 5 ms.

These values are also found to be comparable to the measured results, as shown in Figs. 13 and 14 and summarized in Table 5. The delay parameter is of primary importance in radar systems, and any delay could be taken as Doppler shift. As the optical delay is deterministic, it can be compensated in an efficient manner.

5. Digital signal: measured results and discussion

Digital signals are used in radar systems for control and monitoring purpose. These signals may vary in their bit-rate and duty cycle. The measured result of direct modulated digital signal (Fig. 1) was found to be similar to that of the RF signal, where the insertion loss associated with RoF transmit/receive modules were replaced with the conversion losses of DFB laser and detector.

Signal distribution in a large array demands the use of optical amplifiers to compensate these losses incurred for splitting a signal to a large number of transmit/receive modules. These losses increases with splitting ratio. The splitting loss can be computed as \( 10 \log N \), where \( N \) being the splitting ratio, i.e., 1:64, can cause a signal attenuation of 18 dB along the link. Thus optical amplifiers are used to boost the signal level. Er-doped fiber amplifiers (EDFA) is commonly used for this purpose. But it was observed that the digital signals suffer from transient effect with saturated EDFA as reported in Refs. [17,18]. Additional links may require gain flattening circuits based on the application. Singh et al. [19] presented a Raman-EDFA hybrid optical amplifier configuration. This amplifier configuration provides a flat gain of greater than 10 dB without any gain flattening circuits. But our work focus on variable transients observed with different duty cycle signals. This can degrade the digital signal transmission through fiber link.

A configuration shown in Fig. 16 is used to analyse the transient effect while amplifying the digital signals in the optical links. A 1530 nm laser diode (1 mW) is modulated by a 2 kHz digital signal. Except for EDFA, this set-up is consisted by the components available as parts of a commercial WDM test unit, which is capable of generating variable duty cycle pulse signals. The laser output is amplified using an EDFA operating in the saturation region with a pump power of 30 mW (980 nm). EDFA used is 10 m in length, Er lifetime is

| Table 4 |
| Loss budget of WDM link. |
| No. | Component | Insertion loss/dB |
| 1 | RoF transmitter module | 9 |
| 2 | Wide band AWG mux | 4.5 |
| 3 | Wide band AWG demux | 4.5 |
| 4 | RoF receiver module | 8 |
| Total loss | 26 |

| Table 5 |
| Delays for various test cases. |
| Signal type | Delay in 150 m long fiber/μs | Delay in 500 m long fiber/μs | Delay in 1000 m long fiber/μs |
| NLFM | 0.8 | 2.52 | 5 |
| Pulsed | 0.8 | 2.56 | 5 |

Fig. 15. Delay of pulsed RF signal with fiber length of 1000 m.

Fig. 16. Schematic diagram of experimental set-up used for EDFA transient effect measurement.
10 ms, Er ion density is $2 \times 10^{25} \text{ m}^{-3}$, numerical aperture is 0.24, core radius is 2.2 µm, and Er doping radius is 2.2 µm. The output is then passed on to a photo detector of WDM unit, and the electrical output is observed using a DSO.

Fig. 17 shows the transient effect observed in the output digital signal. The spikes occurring at the output pulses are due to transient effects. As the digital signals used in radar system are primarily used for control and synchronizing, any change in signal characteristics can seriously degrade the beam formation and radar operation.

Additionally, the pulsed signals used for synchronization are produced based on a transmit waveforms that are random in nature and have different duty cycles. The transient effects for different duty cycles are simulated and is shown in Fig. 18. It can be observed that the transient peaks and slope decrease with the increase in duty cycle, which can be explained to be due to greater time available for EDFA gain recovery. These transients are following an exponential curve mentioned in Ref. [13]. The mathematical derivation of the same is not included in this paper.

Fig. 17. Measured transients for 2 kHz pulsed signal - input (yellow) and output (blue).

Fig. 18. EDFA Transients with 10, 20 and 50% duty cycle (2 KHz pulsed signals, pump power at 60 mW).

In addition, it was observed that the effect of transients can be reduced by multiplexing an additional signal, with a complementary pulse, along the link with a nearby wavelength (Fig. 20).

Fig. 19 shows the measured transient result for a digital signal with pulse width of 300 µs and period of 500 µs.

6. Conclusions

WDM-based optical networks are preferred over the conventional signal distribution schemes owing to their physical compactness, low loss, light weight and immunity to EMI. Conventional signal distribution network adds considerably to the system complexity and bulkiness of the active phased arrays. It makes the system massive and demands high capacity drive mechanisms for rotary joints. This paper explored the feasibility of using optical WDM link for distribution of different types of RF and digital signals, hence making the system light and agile. The RF signals like CW, pulsed CW, and NLFM waveforms generated from a radar transmitter was used for experimental measurements. The results were
observed with a finite attenuation due to various component losses incurred in the link, irrespective of the input signal used. The amplitude variations for continuous wave signals were verified using the simulation results. Since the link loss is fixed, for a particular network it can easily be compensated by using the amplifiers in the electrical or optical domain.

The experimental results of NLFM waveform was further verified for side lobe requirements by using pulse compression (PC) techniques. The experiments were also repeated with various fiber spools. The results were observed with a delay proportional to the length of the fiber spool. Therefore, delay and attenuation, being deterministic parameters, can be compensated based on the application requirements.

Further, the paper also discussed about the transient effects associated with digital signals of variable duty cycle. This transient effects can be reduced by adding an additional complementary signal in the WDM link.

This kind of optical distribution helps in the generation of radar signals outside antenna arrays and their distribution through optical rotary joints. Thus it helps in providing a solution free from EMI/EMC related issues.

References