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Analogue RF over Fibre Links for Future Radar Systems

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ABSTRACT

The distribution of analogue RF signals within a high performance radar system is challenging due to the limited space available and the high levels of performance required. This work investigates the gain, linearity and noise performance that can be achieved by an externally modulated direct detection link designed for operation up to 20 GHz using commercially available components. The aim was to assess the suitability of such links for use in future radar systems. Good correlation has been shown between modelled and measured results demonstrating that the performance should satisfy the linearity requirements for many radar applications.

Keywords: RF over Fibre, Radar, Signal Distribution

1. INTRODUCTION

1.1 Introduction

One of the challenges in the design of future radar systems will be the distribution of an ever increasing number of RF signals within the ever decreasing Size, Weight and Power (SWAP) budgets available on the platform. One solution which could help future systems meet these requirements is the distribution of these signals over an analogue fibre optic link. RF fibre optic links offer an alternative to traditional copper coaxial cable links due to their significantly lower loss, lower weight and improved immunity to electromagnetic interference. Initial research into RF photonics was primarily for defence applications. However, difficulties in overcoming some of the implementation challenges meant that link performance was not good enough for sensitive high linearity applications [1]. Since this time there has been a high level of interest in this technology for commercial applications such as the telecommunications industry. This has driven the development forward and high quality and reliable components are now available. This has in turn led to renewed interest from the defence industry. In the last few years, work in this area has been published by several major defence institutions including Thales, Lockheed Martin, Northrop Grumman and US and European defence agencies [2-5].

The aim of this work was to investigate whether RF over fibre could be a suitable replacement for coaxial cable in some areas of future radar systems. An externally modulated direct detection link was designed and built using commercially available components. This was used to demonstrate that the performance of such links can be predicted via modelling, that the achieved performance is suitable for some radar applications and that the SWAP is potentially competitive.

1.2 Background

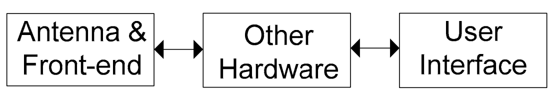

Figure 1-1Radar equipment is split between three key areas within the system

A radar system transmits a signal and monitors the environment for reflections of this signal, these return signals are then analysed. In its simplest form a radar system consists of an antenna, some transmit circuitry, some receive circuitry and some means of processing the signals. Due to space constraints within some systems this hardware may be split into several sub-units. Any degradation in performance caused by the RF interconnect between these sub-units directly affects the performance of the radar and limits the range or resolution to which objects may be detected. The link must cause no detrimental effect on overall system performance (even when subjected to harsh thermal and vibration profiles) and provide a significant advantage in the SWAP budget trade-off compared to existing solutions in order to be viable.

There are three types of signal which may require distribution through the aircraft: receive (Rx), transmit (Tx) and reference signals (local oscillator (LO) and clocks (CLK). The most challenging scenario is typically the receive signals as they are often low amplitude, can have a relatively broad bandwidth and require minimal additive and spurious noise. Like for like replacement of RF cabling within an existing radar systems would require the link to have approximately 10 dB loss, 10 dB noise figure (NF) and minimal effect on linearity for a signal at around -40 dBm for link of approximately 10 m in length. However, there is scope to adjust the gain distribution within future systems, so these numbers have some flexibility. The spurious free dynamic range (SFDR) performance required would be a minimum of 75 dBc

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SFDR with desired performance of over 100 dBc. Assuming a -40dBm output from the link with thermally limited noise at 30 °C, this equates to 114.4 dBc.Hz$^{2/3}$ minimum with 122.7 dBc.Hz$^{2/3}$ desired performance.

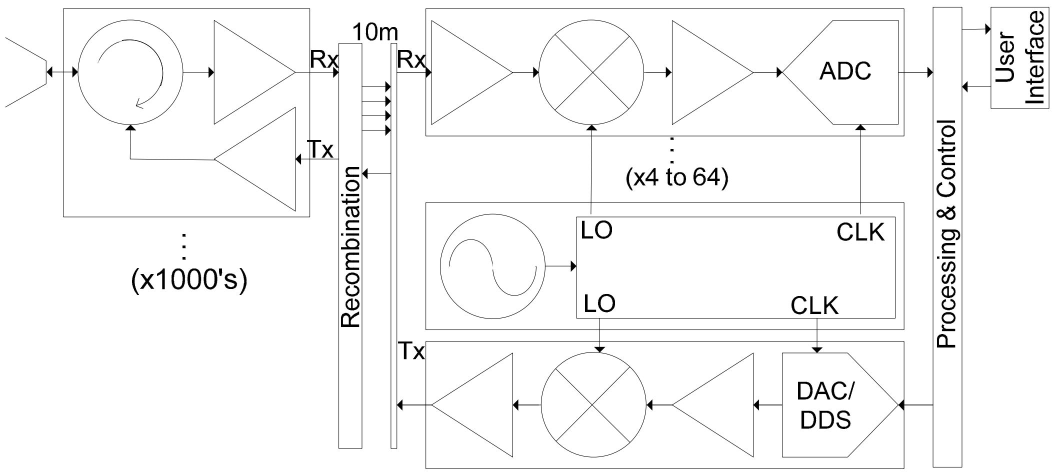

Figure 1-2 Simple Radar block diagram

High performance RF over fibre links rely on low noise, high power lasers; highly efficient modulators; and high power, linear photo-detectors. Due to developments in semiconductor based lasers and components it is now possible to design systems with higher performance, much better stability and smaller size than previously[1]. Williams' survey of pre 1990 RF photonic research [6] found that 60 dBc.Hz$^{2/3}$ SFDR could be readily achieved but it was extremely challenging to improve upon this. Links also typically had very high NF (20 to 40 dB) and high levels of loss (10 to 30 dB). More recently links have been reported with NF of as low as 5 dB, and other links with SFDR as high as 130 dBc.Hz$^{2/3}$ [5, 7]. We carried out a survey of complete commercially available RF over fibre links with RF bandwidths of around 20 GHz. The NF of these links ranges from 5 dB up to about 40 dB with gain values ranging from +11 dB to -30 dB, the SFDR quoted is up to 116 dBc.Hz$^{2/3}$.

Table 1- Summary of link reported RF over fibre link performance

	Gain (dB)	SFDR (dBc.Hz$^{2/3}$)	NF (dB)
Pre 1990 [6]	-10 to -30	60	20 to 40
Amplifier-less links up to 2014 [5, 7].	Some have positive gain	Up to 130	Up to 5
Our survey of commercially available links (~2014)	+11 to -30	Up to 116	5 to 40

2. METHODS

2.1 Introduction

The amplitude modulated (using an external Mach Zehnder Modulator), direct detection (p-i-n photodiode) link was selected for this work as it is expected to give good linearity and noise performance and can be constructed using commercially available components. It is comprised of three key components, a laser source, a modulator to perform the electrical to optical conversion, and a photodetector to perform the optical to electronic conversion. Such links are well understood and the key performance metrics can be predicted based on relatively simple equations [8].

We have implemented a simple model of the link in Matlab with the aim of demonstrating that the performance of an experimental link can be predicted, and hence in future allow such links to be designed appropriately for the application. Based on input device parameters found readily within component datasheets and power levels within the link our model predicts the gain, output third order intercept point (OIP3) and noise figure (NF) of the link. The link was initially modelled at quadrature bias, the point of maximum RF gain. This occurs at the mid-point between the minimum and maximum optical power out of the modulator. As alternative bias points may offer a better compromise between OIP3 and NF, the model was later extended to allow other bias points. This model can be used as a component within wider RF system modelling within specialist RF modelling tools.

2.2 Gain Modelling

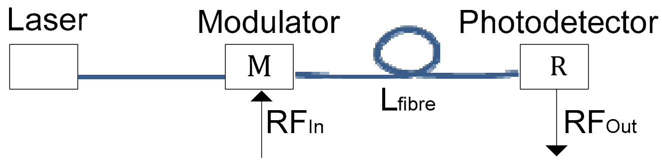

Figure 2-1Basic Externally Modulated, Direct Detection RF over Fibre Link Block Diagram

The gain of the link is defined by the efficiency of the conversions between the electrical and optical domains. Namely, the efficiency of the modulator, M (Watts/Amp), and the responsivity of the photodetector, $\mathcal{R}$ (Amps/Watt). The optical loss within the link must be accounted for (L_{Fibre}), this is multiplied by a factor of two as the RF power is proportional to the square of the optical power. The RF input is assumed to be a sinewave, as such there is a sqrt(2) conversion from r.m.s. voltage to peak-to-peak voltage. Finally, the effect of impedance matching must also be taken into account. In the case that all input and output resistances are 50 Ω this would simplify to a factor of 1/2. In this setup it was found that a factor of ¼ was required instead, this is still under investigation.

$$Gain = 20.\log_{10}\left(\mathcal{R}.M.\frac{1}{2}.\frac{1}{2}.\frac{1}{\sqrt{2}}\right) - 2L_{Fibre} \qquad (dB)$$

Equation 1: Link gain equation, based on [8]

It is clear that the highest link gain can be achieved by selecting components with the highest RF efficiency and by minimizing the optical loss of the link. The photodetector responsivity is defined within device datasheets. For a Mach-Zehnder modulator M is derived from the optical input power level to the modulator, P_{opt}, the modulator's minimum optical loss, M_{loss}, and difference between the bias voltage that gives the minimum and maximum optical power out of the link, V_{π}. Again, it is assumed that R_{mod}, the modulator's resistance is 50 Ω. It is clear that the modulator's efficiency is maximized for high P_{opt}, low M_{loss} and low V_{π}. This equation defines M at quadrature (the point of maximum RF gain). This can be multiplied by $\sin(\theta_{Bias})$ in order to predict the RF gain at other bias points.

$$M = \frac{\pi * P_{opt} * M_{loss} * R_{mod}}{2 * V_{\pi}} \qquad (W/A)$$

Equation 2: Modulator efficiency equation [8]

2.3 Linearity Modelling

In a radar system with a heterodyne architecture it is typically the third order nonlinearity that is of most concern rather than the second order nonlinearity. The third order products fall within the bandwidth of interest, whereas the second order ones can typically be removed by filtering. The third order distortion is minimised at the points of minimum and maximum optical transmission due to the low gain at these points. It can be seen from equation 3 that higher V_{π} leads to increased OIP3, directly contradicting the desire for low V_{π} to achieve high gain. The third order limited SFDR (in dBc or dBc.Hz[23]) can be calculated using equations 4 and 5.

$$OIP3 = 10 * \log_{10}\left(\frac{4 * V_{\pi}^{2}}{\pi^{2} * R} * 4\right) + Gain + 30 \ (dBm)$$

Equation 3: Link OIP3 equation, based on [9]

$$SFDR_{dBc.Hz^{2/3}} = \frac{2}{3} * (OIP3_{,dB} - P_{noise,out,dB.Hz})$$

Equation 4: SFDR (dBc/Hz^2/3)

$$SFDR_{dBc} = 2 * (OIP3_{,dB} - P_{RF\_out})$$

Equation 5: SFDR (dBc)

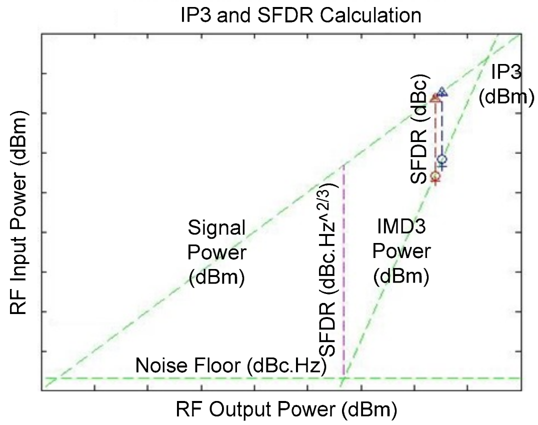

Figure 2-2 SFDR Theory Diagram

2.4 Noise Modelling

There are three key types of noise which contribute to the total noise on the output of an RF over fibre link: thermal, shot and optical. Thermal noise occurs due to the thermal agitation of charge carriers in electronic circuits and at room temperature (~30 °C) has a spectral density of -174 dBm/Hz. The dominant source of thermal noise in the link is due to the photodetector, the level does not vary with detector current. The second source of noise is shot noise, this occurs due to the random nature of the incident photons, it is independent of both temperature and resistance but varies with photocurrent. Optical noise is primarily due to the relative intensity noise (RIN) of the laser and is converted to RF noise proportional to the square of the optical power level at the photodetector.

$$N_{thermal} = 10.log_{10}(k * T * 1000) \quad (dBm/Hz)$$ Equation 7: Thermal noise floor (derived from [8])

$$N_{shot} = 10.log_{10}(2 * q * I_{PD} * R/4) \quad (dBm/Hz)$$ Equation 8: Shot noise floor (derived from [8])

$$N_{RIN} = 10.log_{10}\left(({I_{PD}}^2/2) * 10^{\left(\frac{P_{opt_{PD}}+RIN}{10}\right)} * R/4\right)$$ Equation 9: RIN noise floor (derived from [8])

At different optical power levels different noise sources will dominate. Generally the best performing links (in SNR terms, with the modulator biased at quadrature) are operating in the region in which the optical noise is dominating, i.e. with relatively high photodetector currents. The effect of increasing the bias point above quadrature is to attenuate the RIN or shot noise dominated noise, and hence to improve the link noise figure. For systems in which the second order distortion can be filtered out there will be an optimum modulator bias point above quadrature and the transmission maximum at which the noise is minimised but the gain has not reduced too significantly [8]. This optimum point represents the balance between third order distortion, noise figure and gain which best meets the link's performance requirements.

2.5 Basic Link Design

Our experimental link was designed based on commercially available components with an aim of minimizing the link loss without the use of either optical or electrical amplification. An operating wavelength of around 1550 nm was selected, due to its low loss and the ready availability of suitable components. A distributed feedback (DFB) laser was selected as the source. These operate on a single optical mode so have no side-modes, minimizing the chances of introducing unwanted spurious to the system. These devices can also be manufactured with RIN levels well below the shot noise floor and low linewidths. The selected device is a 40 mW InGaAsP/InP DFB laser module with >-155 dB/Hz RIN. Lithium Niobate Mach Zehnder modulators with low V_π typically achieve the best combined gain and linearity performance [10]. However, the consequence of the low V_π is that even small fluctuations in bias voltage may have a great impact on RF performance so good bias control will be essential. The selected device operates up to 20 GHz, has a V_π of ~1.2 V and optical loss of 4.68 dB. Alternative modulation techniques will be considered in future work.

Commercially available p-i-n photodetectors are now capable of handling significantly higher power levels than they were previously, which has led to significant improvements to the link gain [10]. A highly efficient InGaAs p-i-n photo-detector with a responsivity of 0.92 A/W was selected for this link. However, it should be noted that this device has a relatively low maximum optical input power level of 10 dBm, which limits maximum achievable link gain. In this setup a variable attenuator was inserted in the link between the modulator and photo-detector to reduce the optical power level to a suitable level. Photodetectors with slightly lower responsivity, but higher power handling capability will be considered for future work, as will balanced photo-detection. Balanced links transmit two complimentary versions of the signal which are detected separately before being combined, allowing cancellation of the optical noise.

Electrical amplifiers can be added before and after the link in order to minimize the effect of the link on the system's noise figure and linearity. A low noise pre-amplifier will reduce the effect of high link noise figure on the system noise figure. A high IP3 post-amplifier will reduce the impact of the link linearity on the system linearity. In combination, the resulting cascade may be designed to minimize the effects of the link on system performance.

3. RESULTS

3.1 Link SWAP

One of the aims of this project is to demonstrate that RF over fibre links can be built with suitably small size, low weight and low power consumption for the application. It is readily apparent that the fibre itself is far smaller and lighter than coaxial cable. The inherent immunity of fibre to EMI and crosstalk should make the use of multi-fibre cables possible leading to even greater SWAP reduction. The original link consisted of coaxial cable, connectors and in some cases a low noise RF amplifier. The replacement fibre link contains single mode fibre instead of coaxial cable and three additional active optical components, the laser, the modulator and a photodetector. The components for our link were selected to achieve high performance rather than for low SWAP.

Table 2- SWAP of key link components

	Laser	Modulator	Photodetector	Complete Link
Package Size (mm)	66 x 64 x 20	115 x 16 x 11	18 x 13 x 8	/
Package Volume (cm^3)	84.48	20.24	1.87	106.6
Power Supply	5 V	Bias only	5 V bias	~1.5 W

The laser used in our link is a module containing the laser, thermal control and power circuitry. This was selected for ease of use, alternative DFB lasers are available within standard butterfly packages (volume ~4 cm^3), but the power supply and thermal management would have to be provided externally. The volume of the three key components (not including fibre, connectors, attenuators) is 106.6 cm^2 and the power consumption during normal operation ~1.5 W. This is a significant improvement over early RF over fibre links which used solid state lasers. This link has relatively low SWAP, however it may not be enough for future radar systems with increased numbers of channels and extremely limited SWAP budgets. For multiple links it is possible that some components can be common, providing a further SWAP saving. For receive signals the same laser could be used to drive multiple links, each with their own modulator and detector. For LO/clock distribution, a single laser and modulator could be used for each signal, and a photodetector at each recipient point.

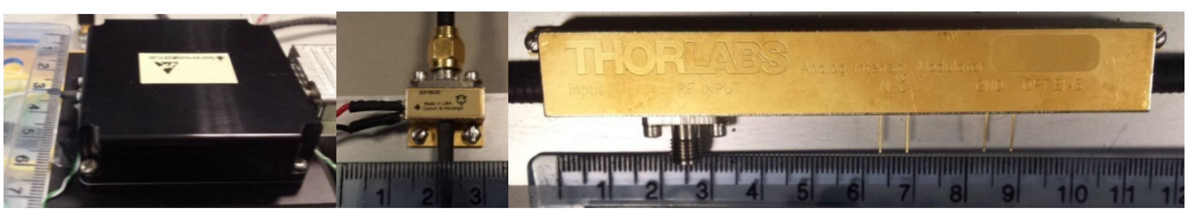

Figure 3-1 a) Laser, b) Photodetector, c) modulator

All of the components selected are semiconductor based devices so are relatively compact, however they are implemented using different materials making integration challenging. A lower SWAP link could be constructed with the laser and modulator combined within a single butterfly package. Using components available today this link would have reduced RF performance compared to our link, but the volume of the three key components would be just 5.9 cm^3. The field of integrated photonics is however developing at a fast rate. Work is also in progress to develop 'invisible links'. Namely the active components would be embedded within the connectors and the link would appear to the user much like a simple coaxial cable with additional power connections. This would provide easy installation and remove any need for maintenance or cleaning of the fibre [11]. The majority of this work is currently focused on digital rather than analogue links though and it may be some time before the performance of such highly integrated photonics is adequate for our application.

3.2 Comparison of Experimental and Modelled results

The link was operated at around 9 GHz. The link gain, OIP3 and NF were measured initially at quadrature bias, and later for a sweep of V_{bias} from 0 V to 3 V in 0.1 V steps. Measurements were carried out within a thermal chamber with temperatures of -10, 10, 30 and 50 °C. The variation in optical power level with a change in V_{bias} was modelled. The V_{π} and V_{offset} values for the model were adjusted to ensure a good match to the experimental results, 1.12 V and 1.22 V respectively for the 30 °C dataset.

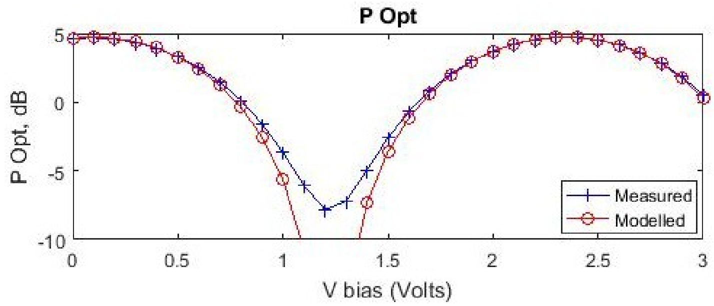

Figure 3-2 Optical Power Level with changing modulator bias voltage

The gain and OIP3 were then measured and modelled; the results are shown in Figure 3-3 below. OIP3 is typically measured by inserting two signal tones into the DUT, measuring the third order intermodulation on a spectrum analyser and calculating the OIP3. For this setup it was difficult to measure this directly due to the high levels of link loss and limited dynamic range available on the spectrum analyser. Instead a pre-amplifier and post-amplifier were added to the setup, the OIP3 of this setup measured, and the link OIP3 derived from these values. A very good match has been achieved between measured and modelled results for both parameters.

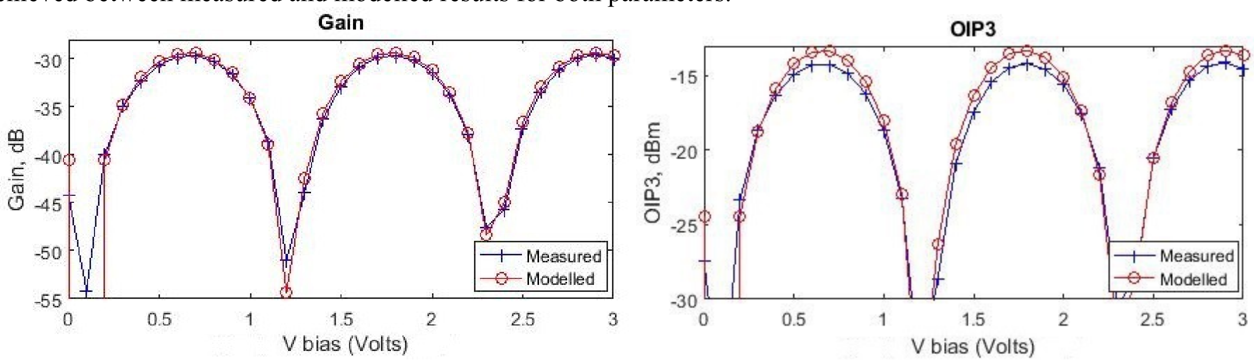

Figure 3-3 a) Link Gain with changing modulator bias voltage, b) Link OIP3 with changing modulator bias voltage

FFT plots captured from the setup including the link, pre and post amplification and an RF filter are shown below for a two tone input. For an input signal level of approximately -40 dBm, 73 dBc SFDR is achieved, limited by the third order intermodulation products. For the same signal level the highest other spur leads to an SFDR of 75 dBc within the 300 MHz RF filter bandwidth.

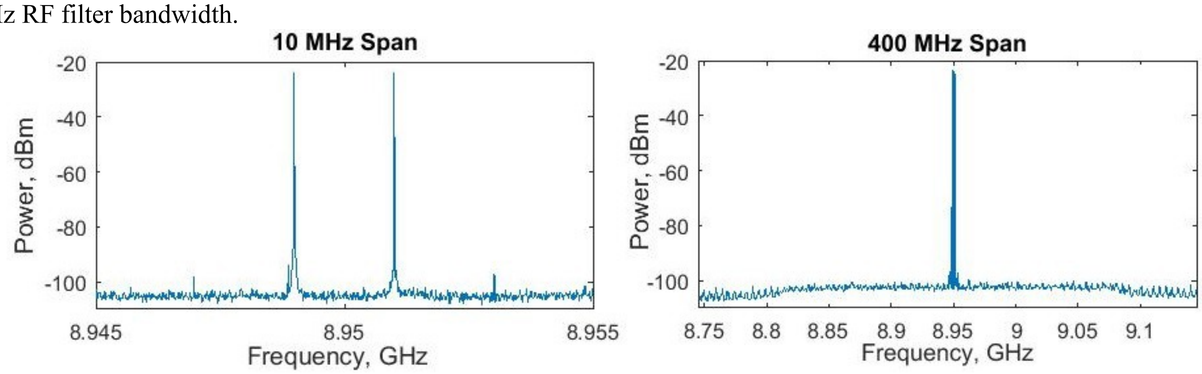

Figure 3-4 Output from the link with pre and post amplification captured on a spectrum analyser

The expected contribution of each source of noise has been calculated for this link and is shown in Figure 3-5 below. In the area of most interest (around peak RF gain) shot noise dominates this link. Whilst the peak RF gain (quadrature points) were found to be ~0.7 V and ~1.8 V, the minimum noise level (low bias point where shot noise level meets thermal noise) were found to be between 1 V and 1.45 V. The laser was selected for its low RIN level, and it is expected that in the V_{bias} regions of interest this is negligible for this operating optical power level. The situation may change if the link optical power level is changed, for example if the photodetector is replaced with one that can handle higher power levels.

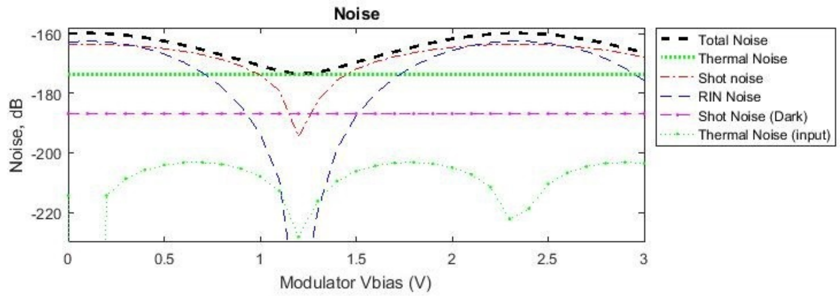

Figure 3-5 Model of link noise sources

Due to the high link loss it was not possible to measure the link NF directly. Instead it was derived from a measurement including pre- and post- amplification. A comparison of the link NF measurement and modelling is shown in Figure 3-6. The traditional Y-factor method was used for this measurement: a noise diode is connected to the input of the setup, and the noise power level at the output measured with the diode switched off, and again with it switched on. The areas marked in grey on the graph below are disregarded there not a large enough difference between the 'noise on' and 'noise off' values for the measurement to be reliable. The areas in which the measurement is valid coincide with the regions of maximum RF gain. With the exception of one outlying result, the match between the measurements and model appears close for low bias voltages, but the difference increases as the voltage increases.

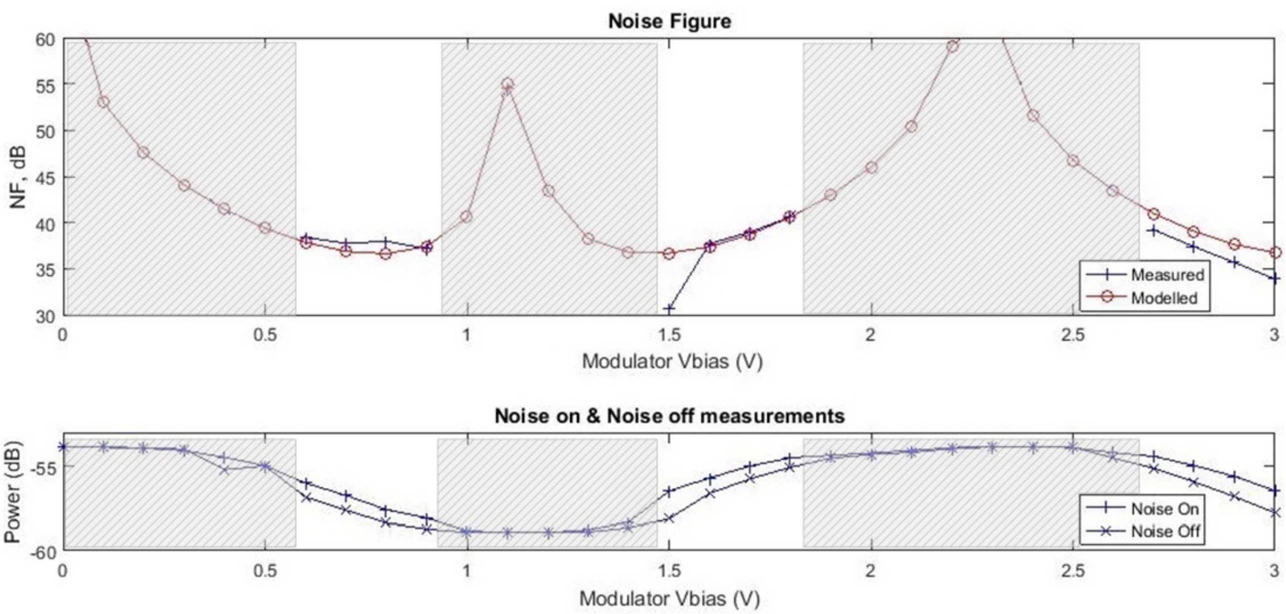

Figure 3-6 a) Noise Figure with changing modulator bias voltage, b) Measured data with noise diode on/off

The results for all three measurements are summarised in the table below, both at quadrature and at a low/high bias position. The measured and modelled results agree to within 1dB for Gain, OIP3 and NF. It should be noted that the measurement uncertainty of the RF power meter used was +/- 0.25 dB.

Table 3 – Comparison of measured results with modelled for four modulator bias points

Vbias	0.7 V (quadrature)			1.8 V (quadrature)			0.9 V (high bias)			1.6 V (low bias)		
	Meas	Mod	Diff	Meas	Mod	Diff	Meas	Mod	Diff	Meas	Mod	Diff
Gain (dB)	-29.69	-29.43	-0.2616	-29.66	-29.39	-0.27	-31.66	-31.51	-0.15	-30.88	-30.53	-0.35
OIP3 (dBm)	-14.23	-13.34	-0.8912	-14.18	-13.32	-0.86	-16.2	-15.42	-0.78	-15.41	-14.44	-0.97
NF (dB)	37.75	36.87	0.88	40.6	40.55	0.05	37.15	37.41	-0.26	37.71	37.38	0.33
SFDR (dBc.Hz2/3)	101.1	102.1	-1.0	99.3	99.7	-0.43	101.5	101.8	-0.25	101.2	101.8	-0.63

3.3 Thermal Sweep

Operation in harsh environments creates challenges not faced by most commercial applications. Additional shielding and protection will be required for use of fibre and components. The requirements are well understood. Military standards exist to define their requirements and there are a number of manufacturers of such cables and connectors . There have also been significant improvements in the environmental packaging of optoelectronic components, some are housed in small hermetically sealed packages and are capable of operating over the full industrial temperature range.

The link would be required to continue to operate reliably despite being subjected to significant thermal variation and harsh vibration profiles. The main change to the link's performance with temperature is that the optimum modulator bias point changes. This behaviour is well understood and can be compensated for with calibration circuitry. In a radar system there are typically programmable devices such as FPGAs within which such calibration routines could be implemented, meaning that the hardware overhead would be minimal. If the radar operates in pulses or bursts, it is likely that the calibration can occur between bursts and the thermal change is likely to happen at a far slower rate.

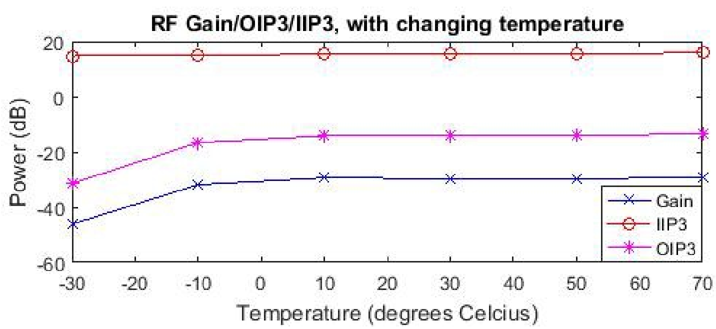

Figure 3-7 a) Link gain/OIP3/IIP3 at quadrature bias with changing temperature

The gain and OIP3of the link were measured for the same V bias sweep as before at a number of temperature points. The results at quadrature bias are shown below. Gain and OIP3 are constant with temperature, except at very low temperatures (which are below the specified operating range of the modulator). Vibration of such links has not yet been studied as part of this work, although the intention is to do so in the future. The effects of vibration on optical components and fibres have been studied [12] and RF over fibre links have been flown successfully by others [13].

4. CONCLUSIONS

In this work a 20 GHz externally modulated direct detection RF over fibre link has been constructed from commercially available components and evaluated for use in a radar system. The link consists of three semiconductor based components: a low RIN DFB laser, a low Vπ Mach Zehnder modulator and a high responsivity p-i-n photodetector. In such an application low SWAP is essential. The volume of these three components is ~ 106 cm^2 and the power consumption ~ 1.5 W. The laser selected for this demonstration is packaged within a module containing thermal control and power supply conditioning for ease of use. There may be alternatives which would allow the link SWAP to be reduced further. Advances in integrated photonics also show promise for lower SWAP in the future, provided the performance continues to improve.

A model of the link has been implemented based on the traditional equations for such links. The modelled and measured results for Gain and OIP3 match to within 1 dB, and NF within 2 dB. This model has been implemented in Matlab, and later used within Keysight's SystemVue tool for future modelling of the link within the context of the wider RF system. For a 9 GHz analog input signal the link achieved a gain of -29.63, NF of 37.75 and OIP3 of -14.23 at quadrature bias.

This equates to an SFDR of 101 dBc.Hz$^{2/3}$. It has been demonstrated that with pre and post amplification this level of performance is good enough to achieve 73 dBc third order limited SFDR for a -24 dBm output signal. There were no other spurs worse than 75 dBc within a 300 MHz bandwidth of the signal. For this link the gain is primarily limited by the low optical power handling capability of the photodetector. The output noise is shot noise limited, a reduction in optical power level would decrease this noise source, but also reduce the link gain.

Demonstrations of other links that have been published have achieved lower NF (as low as 5 dB) and higher SFDR (some above 130 dBc.Hz$^{2/3}$). A number of different techniques have been utilized to achieve this, balanced photo-detection, dual parallel Mach Zehnder modulator and others. Many or these links incorporate custom components to enable this level of performance. It should be possible to achieve the target 100 dBc SFDR at an output signal level of -40 dBm using a link with 122.7 dBc.Hz$^{2/3}$ SFDR (assuming thermally limited output noise), or even 116 dBc.Hz2/3 (assuming 10 dB above thermal output noise). Finally, the link model was found to be reliable with temperature variation, with the exception of the variation in bias voltage offset (V bias voltage to achieve quadrature operation).

Planned future work includes using the link within an existing Radar system and demonstrating the impact on system performance both through modelling and experimentally. Some investigation of the impact of vibration on the link performance is planned as is the development of an improved link using alternative components/techniques.

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