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Low Cost RF over Fiber Distribution For Radio Astronomy Phased Arrays

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***Abstract*—Arguably RFoF has found wide application in broadband cable TV (CATV) systems and more recently in wireless cell applications. The use of RFoF also has a history in Radio Astronomy (RA) instrumentation. Typically in the distribution of high quality Local Oscillator reference signals to reflector antennas. On the scale of a small number of reflector antennas there are several examples where Directly Modulated (DM) laser diodes or Externally Modulated (EM) RFoF links have been used for wideband RF or IF transmission of the radio astronomy signal bandpass from the receiver package back to a centralized digital signal processing rack. In the last decade the radio astronomy community has developed an appetite for wide field of view, large N phased arrays, essentially N element distributed antenna systems (DAS). The Square kilometre Array (SKA), the Murchison Widefield Array (MWA) and the Australian Square Kilometre Array Pathfinder (ASKAP) all have thousands of receptors. ASKAP in particular is already demonstrating a 6840 RFoF link based DAS architecture with 36 remotely located 12m reflector antennas and RFoF spans up-to 6km. Each reflector having a 188 element L-Band phased planar array feed (PAF) at the prime focus. In this paper we report our development of the low cost RFoF "building block" for the generic RA signal transmission application.**

***Keywords*— ASKAP, PAF, RFoF, DAS, DFB**

I. INTRODUCTION

Radio Astronomy systems are necessarily extremely radio sensitive and electromagnetic compatibility (EMC) is a prime concern. RFoF enables the sensitive front-end receptors with LNA/receivers to be isolated by free space loss from the high clock rate, high radio emissions, digital signal processing back-ends. We have shown this to be economically viable for wideband PAFs over several kilometres of standard single-mode SSMF fiber span.

The separation of the front-end from the backend by RFoF then becomes a pivotal architectural decision. For RF frequencies below 2GHz it is possible to use direct sampling techniques with the latest 12bit ADCs. This obviates any requirement for complex high data transmission digital links as this is replaced by simpler looking RFoF links.
The use of RFoF effectively displaces any coaxial cable, which in practice is limited to about a 50m span at L-band frequencies.

Using optical fiber to connect a front-end provides a high level of galvanic isolation, removal of ground loops and increased lightning protection. Power supplies are still required but protecting a small number of DC power supply conductors is a more tenable problem than protecting hundreds of coaxial connections. Fiber is lightweight, flexible, with a form factor suited to movable reflector antennas with tracking Azimuthal, Elevation and Polarization axis. The temperature co-efficient of single-mode fiber is less than 10ppm/C, and linear, unlike many coaxial cables with dielectric filler. Chromatic dispersion effects of the fiber are minimized by using RFoF at the zero dispersion wavelength 1310nm. Non-linear optical effects including laser wavelength chirp are also minimized.

Our early proof of concept work [6] used low cost VCSEL 850nm multi-mode lasers for 50m multimode fiber spans. Recently the price point of quality uncooled InGaAsP/InP MQW distributed feedback lasers (DFB) at 1310nm with inbuilt optical isolation has made this DFB our component of choice for the optical transmitter. This is complimented by InGaAs PIN diode detectors for the optical receiver Fig.1. The maximum uncooled DFB optical power P_o=4mW (6dBm) and comply to IEC60825 Class 1 standards.

Our RFoF designs are DM direct detection intensity modulation designs suitable for sub-octave and broadband transmission exhibiting a characteristically +/-1dB flat frequency response over any 500MHz range. Our designs have focused on dynamic range, low noise, high gain, amplitude/phase stability, with reasonable input and output impedance match for 50Ω.
For bandwidth distance products less than 10GHzkm we have developed empirical models for RFoF links and applied these successfully in mixed signal end to end RA system designs.

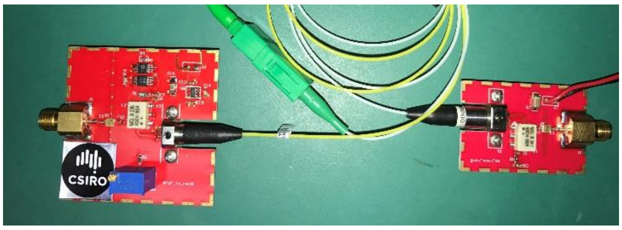

Fig.1 RFoF Transmitter/Receiver pair

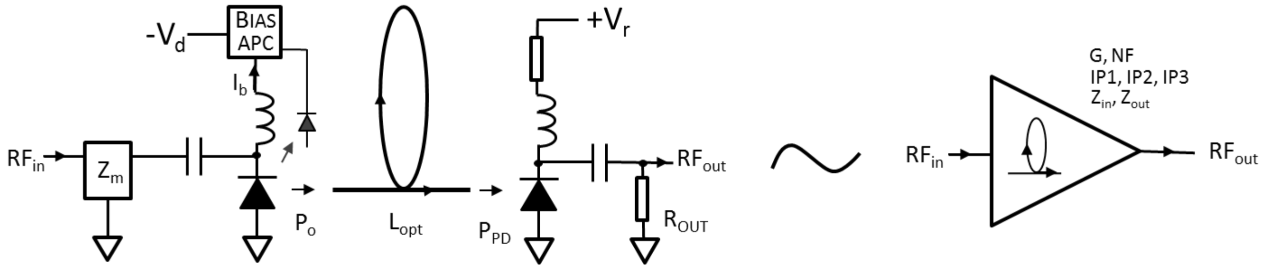

Fig. 2 RFoF Intrinsic Link Model

II. THE INTRINSIC LINK

The intrinsic link we take to be the DFB laser diode, a length of SSMF G652B (SMF28 or equivalent) and a PIN photodiode. The DFB is a grounded anode style. This package assists low impedance RF bonding to PCB ground. A bias "T" package is used to couple forward DC bias current for the DFB. A small reverse bias on the PIN Rx diode reduces junction capacitance for a high frequency response of several GHz. DFB devices have a real input impedance of a few ohms so for purposes of our intrinsic link model we include the 50Ω input matching network Z_m. The DFB package includes a back-facet monitor diode to enable Automatic Power Control of the average optical DFB output power Po = 4mW (6dBm). The RFoF span requirements are typically short (<10km) spans with low optical loss. At 1310nm the fiber loss is typically 0.35dB/km. All interconnects are high optical return loss (ORL). Any residual back reflections into the DFB are attenuated with an in-built single stage isolator. For practical purposes we model the intrinsic link using device datasheets and application of theory as an equivalent amplifier building block shown in Fig.2. The model considers performance over a range of fiber spans with loss L_{opt}(dB). The transmitter requires 6Vdc 30mA power supply (180mW).

A. *Intrinsic Link Trade-offs*

Understanding the trade-offs in DM RFoF links is non-trivial and many parameters are interrelated, a full treatment of which can be found in literature [1].

1) *Gain*

For our purposes we started by considering gain as the most important parameter, devising links with minimal attenuation (highest gain). The link gain is $G_i \propto S_L^2 S_R^2$ where S_L (W/A) is the DFB slope efficiency and S_R (A/W) the PIN detector responsivity. In our trial of suitable commercial DFB devices we have found the slope efficiencies typically in the range $0.15<S_L<0.3$ W/A. The manufacturers PIN responsivity is used S_R (A/W) =0.85A/W at 1310nm.

With L_{opt} =0dB, S_L=0.3W/A and a monolithic 4dB RF pad as the input matching network Z_m, the intrinsic gain G_i= -18dB. Adding 10km of fiber at 1310nm would increase L_{op}t = 3.5dB reducing gain a further 7dB electrical, G_i= -25dB. If S_L =0.15 then the gain would reduce a further 6dB, G_i=-31dB. From a DAS perspective this range in link gain -31dB < G_i < -18dB must be considered in a system design. Intrinsic gain has a significant follow-on impact to intrinsic link Noise Figure and compression point.

2) *Noise Figure*

Intuitively, for a nominal G_i =-25dB the intrinsic noise figure NF_i must be larger than 25dB, NF_i > 25dB, given RFoF involves active components that add noise. The DFB will add relative intensity noise RIN (dBc/Hz), shot noise dBm/Hz with respect to optical receive power and thermal noise at the PIN detector dBm/Hz. We summarize the expressions [7] for these terms with average PIN photodiode current I_{dc} and R_{OUT}= 50Ω.

$$N_{RIN}\,[\text{dBm/Hz}] = \text{RIN}[\text{dBc/Hz}] + 20\log(I_{dc}[\text{mA}]) - 1$$

$$N_{SHOT}[\text{dBm/Hz}] = -168 + 10\log(I_{dc}[\text{mA}])$$

Let $k=1.38\text{x}10^{-23}$ J/K an T=290k at R_{OUT}

$$N_{TH}[\text{dBm/Hz}] = -174$$

$$N_{OUT} = N_{RIN} + N_{SHOT} + N_{TH} \quad \text{in linear terms}$$

By definition: Noise figure $F = \frac{SNR_{in}}{SNR_{out}} = \frac{S_{in}}{KT} \cdot \frac{N_{out}}{S_{out}}$

$$NF[\text{dB}] = 10\log[F]$$

$$= N_{OUT}\,[\text{dBm/Hz}] - G_i[\text{dB}] + 174$$

A model of N_{OUT} noise power spectral density contributions with average photodetector current I_d(mA) are shown in Fig.3. RIN noise tends to be the major noise contributor in a DM link. Low DFB RIN noise is required over the RF modulation frequency range. Datasheets indicate RIN < -150dBc/Hz.

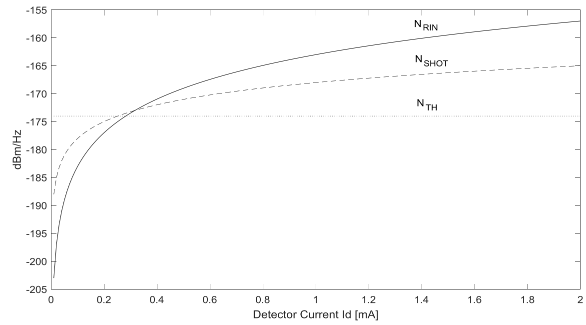

Fig.3 Link Noise Contributions (RIN= -150dBc/Hz)

Assume a 10km link with P_{PD}=0dBm the detector current $I_{dc} = S_R P_{PD} = 0.85$mA ; RIN=-165dBm/Hz in Fig.3; The NF_i = 34dB at 1GHz in Fig.4. Interestingly if RIN < -160dBc/Hz the shot noise begins to dominate. The measurement example shown in Fig.4 has the intrinsic link noise floor rising with increasing frequency up to the DFB relaxation frequency peak. We measure G_i and NF_i versus frequency for fiber spans of 1m and 10km Fig.4 using a 21dB ENR noise source and Agilent N8974A noise figure meter. Results are further corroborated using the twice power additive noise technique [5] given the high noise figures involved.

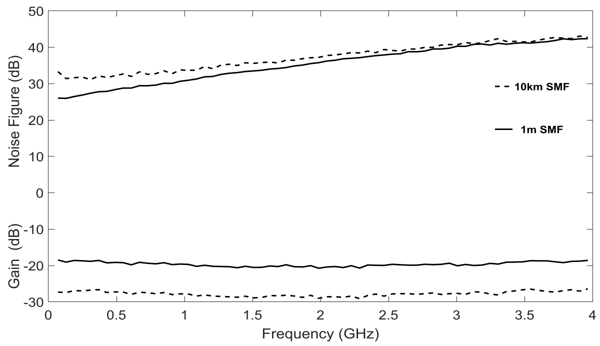

Fig.4 Measured Intrinsic Link NF and Gain

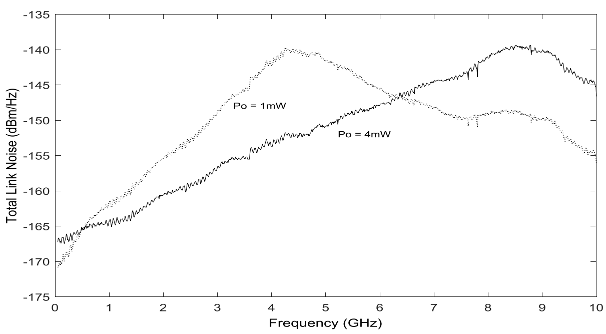

Fig.5 Measured Intrinsic Link Noise

Clearly, based on our measurements, for better noise performance below 5GHz the recommended DFB manufacturers datasheet optical power of Po=4dBm is recommended.

3) *IP1,IP2,IP3 (1m span)*

With a 1m fiber span and link gain of G_i = -20dB the 1dB compression point is measured at the input, IIP_1 = +10dBm and IP_1 = -10dBm.

Results of two tone intermodulation measurements are shown in Fig.6 and Fig.7. The fundamental input tones are f_l=1500MHz (-10dBm) and f_2=1501MHz (-10dBm).

Let $IP_n = P_{out} + \frac{\Delta}{n-1}$ per [3]

Using $f = 2f_2 - f_l$ IP_3 = 6dBm
Using $f = f_2 + f_l$ IP_2 = 8.3dBm

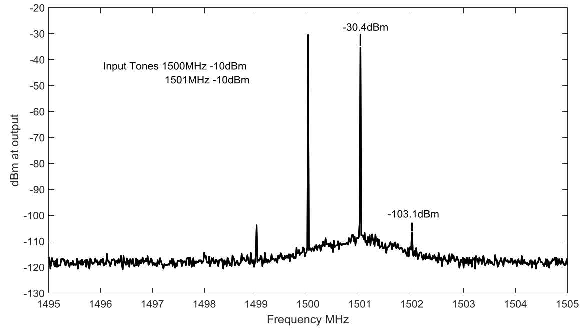

Fig.6 Third order distortion

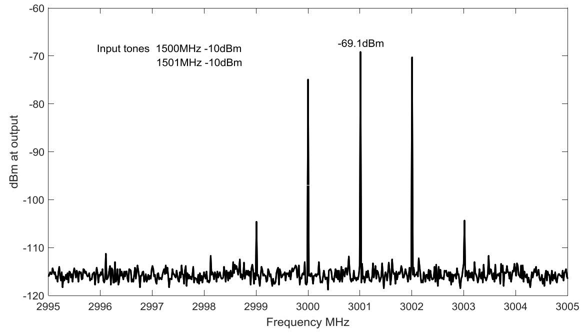

Fig.7 Second order distortion

4) *Dynamic Range (1m span)*

The $DR_n = \frac{n-1}{n}[IP_n - (Noise\ floor\ )]$ per [3]

Where $(Noise\ floor\ ) = (10LogkTB + NF_i + G_i)$ at output.

Let B = 1Hz NF_i = 33dB G_i = -20dB per Fig. 4 for 1m span.

$DR_2 = \frac{1}{2}$[8.3 – (-174 + 33 -20)] = 85dBHz$^{1/2}$

SFDR= $\frac{2}{3}$[6 – (-174 + 33 -20)] = 111dBHz$^{2/3}$

The compression free dynamic range is

$CDR = [IP_1 - (10LogkTB + NF_i + G_i)] =$ 151dBHz

5) S-parameters

The DFB input impedance is typically low (~5Ω), devising low loss compact broadband impedance matching networks remains a challenge. The intrinsic link S-parameters measured by Agilent E5063A vector network analyser is shown in Fig 8.

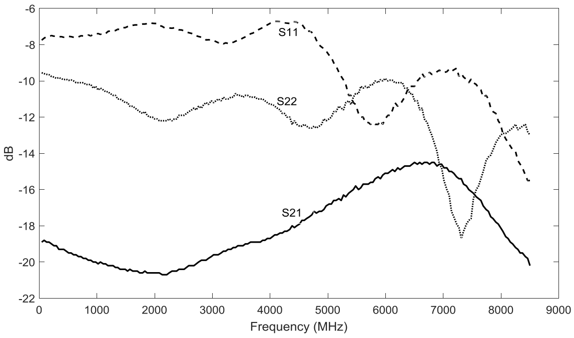

Fig.8 S-Parameter Measurements

For our designs, the S_{11} performance can be further improved increasing the 4dB matching network Z_m to 6dB with commensurate trade-off in S_{21}.

6) Stability with Temperature and Fiber Flex

Radio-Telescopes are inherently amplitude sensitive devices. Measurements of amplitude and phase stability are required over long and short timescales. Long timescale stability (10minutes) is compensated by routine astronomical source calibration. Short timescale stability is more problematic.

A repetitive motion test-jig is used to bend a single strand of SSMF at 300mm radius on a 10sec period, although such a dramatic flexure is unlikely in real telescope scenarios. DSP apparatus and correlation techniques at 1200MHz are used. The amplitude stability is determined to be 0.04dBpp over 10sec Fig.9. Phase stability plots with similar perturbations of 0.2deg pp over 10secs are obtained [5].

Averaging results over a 60sec period stability was 0.001dB and 0.001deg. Over long timescales the temperature co-efficient (laboratory room temperature) of the fiber spool dominates test results and this is found to be less than 10ppm/C.

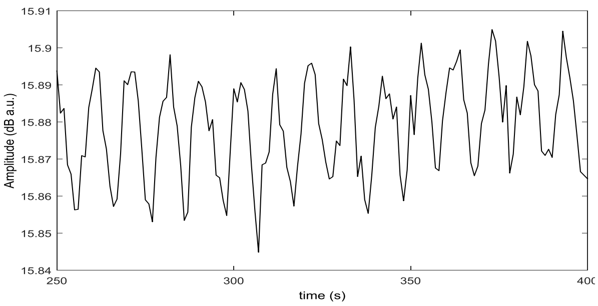

Fig.9 Amplitude Stability Tests of Fiber

Comparing fiber performance with commodity grade low loss 3mm flexible coax showed fiber to have superior stability. For RFoF implementations it is important that robust optical connectors are used. Our experiences with LC/APC, FC/APC and mass termination MTP-12way connectors have been encouraging if connector surfaces are kept clean.

7) RFoF Optical Loss Budgets

Maximizing the PIN photodetector optical power is fundamental to ensure good dynamic range. We allow 0.05dB per splice, 0.5dB per connector and 0.35dB/km for fiber at 1310nm. For field serviceability, the DFB and PIN detector pigtails are connectorized, for a 1km link a minimal optical link loss of 1.35dB should be expected. Since $L_e = 2\,L_o$ dB link G_i is impacted 2.7dB. Recovering the dynamic range by increasing the DFB optical power can offset the reduction in IP1 by the drop in G_i . Eventually the PIN detector will saturate with too higher optical power (~6dBm). A higher RF input power and hence increased system gain is required to maintain the system NF.

8) RFoF Backreflections

Future Radio-telescope phased arrays are likely to entail fixed point to point link configurations. It remains important to ensure low connector count and minimal back reflections in the links. Analysis [1] has shown detrimental effects to RFoF link dynamic range with an ORL less than 40dB . The DFB has in-built 20dB optical isolators and the use of 60dB ORL APC connectors help substantially in this respect.

9) Aging and Temperature Effects

Literature [4] suggests uncooled DFB "lifetime" to be in excess of 70000hrs at 40C case temperature. In the analog context this will refer to a drop in slope efficiency S_L (W/A) of the DFB rather than complete device failure. Anticipating a reduction of 25% in S_L (W/A) with age and elevated temperature is prudent design. Accelerated testing of a large number of DFB links would be required to confirm more specific device data.

III. CONCLUSIONS

We have shown a practical, easy to apply equivalent amplifier model for the RFoF link. RFoF links offer a wide frequency range and sufficient dynamic range for radio quiet locations. In large quantities we have costed components at under $100/link. This potentially satisfies the price sensitive needs for the signal transmission element in a variety of new radio astronomy arrays.

REFERENCES

[1] Cox, *"Analog Optical Links Theory and Practice"*, Cambridge University Press 2004, Chapter 7.

[2] Agilent, *"Fundamentals of RF and Microwave Noise Figure Measurements"* Application Note 57-1

[3] Avigdor Brillant, *"Digital and Analog Fiber Optic Communications for CATV and FTTx Applications"*, Wiley 2008 Chapter 9.

[4] ILX Lightwave Application Notes *"AN#33", "AN#29 Estimating Laser Diode Lifetimes"*,2008

[5] Roberts, *"Stability Measures of MTP12 Connectors and Fiber"*, 2012 CSIRO Internal Documentation.

[6] Beresford, *"ASKAP Photonic Requirements"*, IEEE International Topical Meeting on Microwave Photonics Proceedings ID9108, 2008.

[7] Williams and Urick, *"OFC2014 SC160 Microwave Photonics"*, NRL