

Analog Optical Link Technology for Astronomy Instrumentation

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1 Introduction

In this report the components and performance of analog optical link (AOL) technology and its functioning in RF (phased array) systems are described. It shows the advantages of optical analog link technology and describes the phased array system configurations that will benefit from the application of AOLs. By introducing photonic technology in RF systems, broadband, high(er) frequency operation will be enabled, while at the same time cost savings will be obtained thanks to its low weight, small space envelope and EMI free properties.

To show the functioning and possibilities of AOLs, a detailed AOL description is provided in Chapter 3 and Chapter 4. In the latter, RF engineering information on the functioning and implementation of AOLs in RF systems is provided. Section 3 is concerned with a thorough AOL / RF system assessment. For two popular modulation formats (direct intensity modulation and external intensity modulation) the AOL performance and their functioning in an RF system is determined. It is shown that an AOL can be considered as a regular RF component that is suitable for application in (radio-astronomy) phased array systems.

2 Components for Analog Optical Links

2.1 Introduction

In analog optical links the analog signal is transferred via a fiber-optic link by modulating the optical field that is applied at the input side of the link. For this, a wide range of modulation types are available, each with its own technological characteristics. The most straightforward and widely used modulation technique is intensity modulation. Other available modulation types, like quadrature amplitude modulation (QAM), single sideband modulation (SSB), frequency modulation (FM) and phase modulation (PM), require more complex modulators and/or optical coherence. Although the application of the latter modulation types will cause higher system costs, they are preferred in specific situations thanks to their better performance. In this report only intensity modulation is addressed.

Intensity modulation can be realized both by directly modulating the laser, by varying the laser current (direct modulation) or by applying a modulator in the link after a CW source laser (external modulation). Both types will be addressed below.

2.2 Components for analog optical links

2.2.1 Source Lasers

Various types of diode lasers are available for application in analog optical links. Their wavelengths range from around 800 nm up to 1600 nm.

Also a number of package types are being used. A more complex and expensive type is the butterfly package which is suitable for housing e.g. a laser diode, monitor diode, TEC and thermistor (see Figure 1).

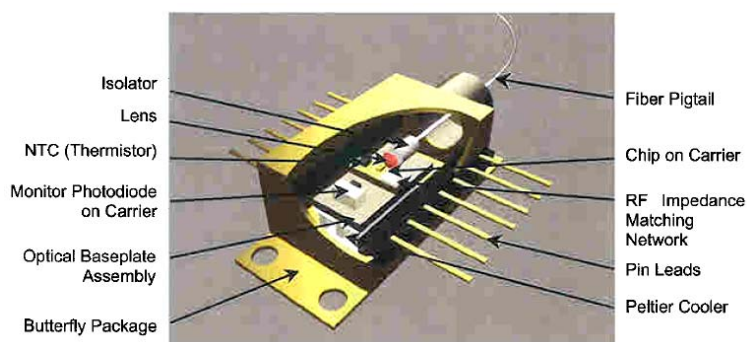


Figure 1 Schematic layout of the butterfly package.

For low cost lasers usually TO-can, coaxial and TOSA packages are applied.

2.2.1.1 Laser types

A number of laser types are suitable for application in AOL systems. The most important are described below. In all types, a laser diode chip is used for the generation of the light. The type of laser is determined by the configuration of this chip.

Fabry-Perot laser

Due to the absence of a laser mode selection scheme in its chip design, the FP laser spectrum consists of a comb of wavelengths in the gain region of the chip. The relative broad spectral width of these longitudinal mode field in combination with chromatic dispersion in a fiber, results in a limited transmission distance for FP laser links, compared to e.g. DFB based links.

Thanks to the simple chip design, the costs of this component are lower than the DFB / DBR costs.

DFB / DBR laser

In this type of laser a grating is used for the selection of a single laser mode. As a result only a single wavelength peak is present in its spectrum. Depending on the quality of the laser very narrow linewidths, in the order of ~1 MHz, can be obtained. As a result, chromatic dispersion issues will play only a very small role in DFB / DBR based links. Due to the complicated fabrication of both the chip and the package this laser type has the highest costs.

VCSEL

The previous laser types have an optical field in the plane of the wafer / chip. VCSELs have a cavity that is perpendicular to this plane. Like the DFB / DBR laser types, distributed reflectors are used for selecting a single wavelength for the output optical field. Apart from the optical output power, which is relatively low, the optical characteristics of the VCSEL are more or less comparable to the optical characteristics of the DFB / DBR types. Thanks to the relatively simple fabrication of this laser type its costs are relatively low.

2.2.2 Modulators

In case external modulation is applied, a modulator is needed for the transfer of the signal from the electronic to the optical domain. Both integrated laser/modulator (EML) components and separate modulators / lasers are available for external modulation links. The performance of an EML based AOL is limited due to the low optical output power of the EML. As a result the use of EMLs in AOL systems is not preferred. More information about the relation between optical power and link performance is given in the next chapter.

Two main types of modulators can be distinguished: Mach-Zehnder Interferometer (MZI) modulators and Electro-Absorption (EA) modulators.

MZI modulator

This type of modulator consists of a photonic integrated circuit (PIC) based interferometer in which the optical path length can be adjusted with the use of one or more electro-optical effects. By changing the length of one of the optical paths in the interferometer the applied light is modulated. The most straightforward MZI modulation type is intensity modulation. Nevertheless, depending on the MZI-PIC layout, also other modulation formats like phase modulation and QPSK modulation are possible. Usually MZI modulators are made on lithium niobate material. Also InP/InGaAsP and polymer based modulators are available.

Modulator related distortion

The MZI modulator has a sinusoid behaviour as function of an applied voltage. By biasing the modulator in the quadrature point all even intermodulation products are suppressed. The strongest spur is the IP3, whose IIP level usually is larger than 25 dBm.

Stability

Due to surface charging effects in lithium niobate modulators, the modulator can drift from its quadrature point at a constant bias voltage level. This effect can be compensated for by using feedback electronics that monitors the output power of the modulator.

Chirp

MZI can also have a very small amount of chirp (compared to direct modulated lasers). The presence of chirp depends on the design of the modulator chip. In x-cut MZI modulators the hot electrode is placed symmetrically between the waveguides of each branch. This shifts the phase in each arm equally, but in opposite directions, which produces zero chirp. However, in the z-cut modulator the electrode is placed directly over one of the waveguides and the resultant asymmetry in the drive produces a non-zero chirp parameter with typical magnitude of 0.7.

Wavelength

Most modulators are built on lithium niobate material. This material has a transparency wavelength window between 330 nm – 5500 nm [3]. As such, this type of modulator could operate within this entire window. However, since the optical propagation properties of the modulator waveguides depend strongly on the wavelength, a specific modulator will only operate properly in a part of the transparency wavelength window.

Optical input power

The maximum optical input power of a MZI modulator is determined by the surface damage threshold, which, for lithium niobate, is in the order of 10 J/cm² [3], resulting in maximum optical input power levels larger than 25 dBm.

EA modulator

In external modulation based telecommunication and signal transport systems, lithium niobate MZI modulators are usually applied as modulator. However, nowadays the electro-absorption modulator gains popularity, thanks to its smaller size, better on-off ratio and easier integratability properties. In spite of all these advantages, one major disadvantage remains its limited maximum optical input power ($P_{op,max}$) level which is in the order of 10 dB lower than the $P_{op,max}$ level of lithium niobate MZI modulators.

An electro-absorption (EA) modulator uses one or more electro-optical effects for absorbing the applied light. By adjusting the amount of bias voltage the absorption level can be adjusted and modulated. The slope of the absorption vs. voltage characteristic is non-linear, resulting in a bias voltage dependent slope efficiency and IM level.

Modulator related distortion

The EA modulator related AOL performance suffers from both IM2 and IM3 distortion. Their levels can be optimized by using the proper bias voltage. The IIM2 and IIM3 levels are ~5 dB below their MZI-modulator counterparts.

Chirp

The chirp level (α -parameter) of an EA modulator is usually in the range between -1 and 1. The actual chirp level depends on the bias. It is found that the measured chirp α -parameter ranges from -0.4 to 0.8 depending on the level of the reverse bias that is applied to the EA modulator.

Wavelength

The electro-absorption properties of an EA modulator are optimal for wavelengths close to the bandgap. As a result the insertion loss of the modulator will strongly increase at shorter wavelengths, causing a limitation of the operational wavelength range of the EA modulator. In practice EA modulators between 1500 nm and 1600 nm are available.

2.2.3 Detectors

For the transfer of the signal from the optical domain into the electronic domain two types of detectors are available: a PIN photo diode and an APD. Both types use a reverse biased diode for the generation of a light intensity dependent current. In an APD (avalanche photo diode), a relatively high reverse bias level is applied resulting in the generation of multiple electrons per photon. In this way a higher detector responsivity is obtained. Since this responsivity enhancement is accompanied by a strong increase in the noise level, causing a reduction of the dynamic range, the application of APDs in AOLs is not very practical. As such, APDs will not be taken into account in this report.

At most relevant wavelengths detectors are available. The speed of a detector is to a large extent determined by the capacitance of the reverse biased pn-junction: the smaller the device the larger the bandwidth. However, by reducing the size of the detector PN junction, the detection efficiency is also reduced, which limits a strong reduction of the detector size. Nowadays photo detectors with a bandwidth towards 500 GHz are being developed [4]. The amount of suppliers of these relatively complex high frequency detectors is very limited. Detectors for the lower (SKA) frequencies are widely available.

3 Analog Optical Link Technology for Astronomy Instrumentation

Within the present day astronomy systems, most of the low frequency analog signal transfer is based on electronic technologies like co-ax cables. In principle, this co-ax approach supports the transfer of signals with frequencies up to about 60 GHz. However, from 1 GHz and up, the application of alternative technologies becomes more attractive, due to the relative high RF losses and a strong frequency dependent RF loss at elevated frequencies and the higher cost of the co-ax cable. A signal transfer technology that solves both issues is analog optical link technology. AOL technology has a flat frequency response over a large frequency range and good, transmission distance independent RF loss and dynamic range properties up to frequencies beyond 60 GHz. Additional advantages of this approach are the low weight, small space envelope and RFI immunity properties of analog optical link technologies.

Within this section the microwave photonic behavior of the two most important analog optical link technology types are described: direct and external modulated analog optical links. External modulation AOLs are treated as an example of a high performance, higher cost AOL type, while the described direct modulation AOL type is a lower cost alternative.

3.1 External modulation based links

Within this type of analog optical link the signal is transferred from the RF to the optical domain with the use of an external modulator. A number of modulation formats are available. Intensity modulation, which will be used as an example in this chapter, is the most straightforward of these formats. The big advantage of external modulation, when compared to direct modulation is the bigger freedom in the design of the link. The most important example of this, is the adjustment of the link gain by varying the optical power in the link: the higher the optical power, the higher the link gain. In the next subsections the RF properties like, link gain, noise and distortion of the analog optical link that will be applied in the photonic tile demonstrator will be described and experimentally determined.

3.1.1 Link gain

The link gain expresses the amount of RF gain that the RF signal experiences when going through the analog optical link. In externally modulated links the link gain depends on the slope efficiency and the responsivity via [5]:

$$\text{Linkgain} = \left(\frac{s_m^2}{R_S} \right) \cdot T_{FF}^2 \cdot (r_d^2 \cdot R_{LOAD}) , \quad (1)$$

In which R_s and R_L are the source and load resistances and T_{FF} the total optical loss in the system.

In classical links the link gain is below -20 dB. These very low gain levels are caused by a small slope efficiency. Since in externally modulated links the slope efficiency depends on the optical power in the system, the link gain can be improved by applying high power lasers. In Table 1 information about the latest and best performing AOL components is given. Using this information, the slope efficiency of the MZM based transmitter [5] and the maximum link gain are calculated. The results of this are depicted in Figure 2.

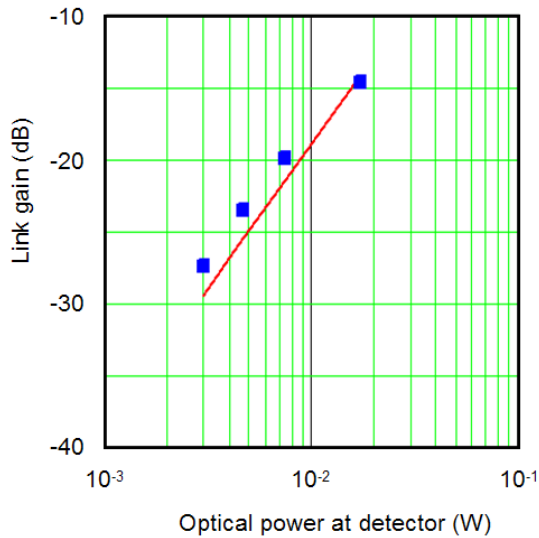


Figure 2 The calculated (red) and measured (blue) link gains as functions of the optical power at the detector.

The calculation shows that at an optical power level of 100 mW a maximum link gain of -12.9 dB can be obtained. However, due to additional optical losses at e.g. interfaces, the actual (measured) maximum link gain is -14.6 dB.

Table 1 AOL component properties

Laser		
	Type	EM4, AA1406
	Optical power	100mW
	RIN level	-170 dB/Hz
Modulator		
	Type	Photline, MXAN LN10
	Insertion loss	4 dB
	V_{π} at 1 GHz	5.5 V
	Input impedance	50 Ω
Detector		
	Type	Agere, R2560A
	Responsivity	0.8 A/W
	Impedance	50 Ω

3.1.2 Noise

In a classical externally modulated link the following noise sources are present [5]:

- Thermal noise
- Shot noise
- Relative intensity noise

Each of these sources behaves differently as function of the optical power at the detector: the first is constant, the second has a linear dependence and the third has a quadratic dependence. Thanks to these different dependences, a number of different noise regimes can be distinguished. In every noise regime a specific noise source is dominant. In Figure 3 the calculated and measured noise as function of the optical power at the detector are given, for an AOL that comprises the components given in Table 1. It shows clearly the mentioned noise regimes. At low optical powers the thermal noise is dominant, while at high optical powers the RIN is the most important noise source. At intermediate power levels (around 10 dBm) the shot noise is the main noise source.

In addition to the calculation results, also the results of noise measurements are given. These results show the shift from thermal to shot noise regime around an optical power of 8 dBm. At the lower optical power levels the calculated noise levels are shifted with respect to the measured noise levels, which is caused by an elevated thermal noise level of -166 dBm/Hz in the signal from the signal generator that acts as a noise floor in the noise measurements. The highest optical power level that can be obtained at the detector is around a optical power level of 12 dBm, at which position the link is shot noise limited.

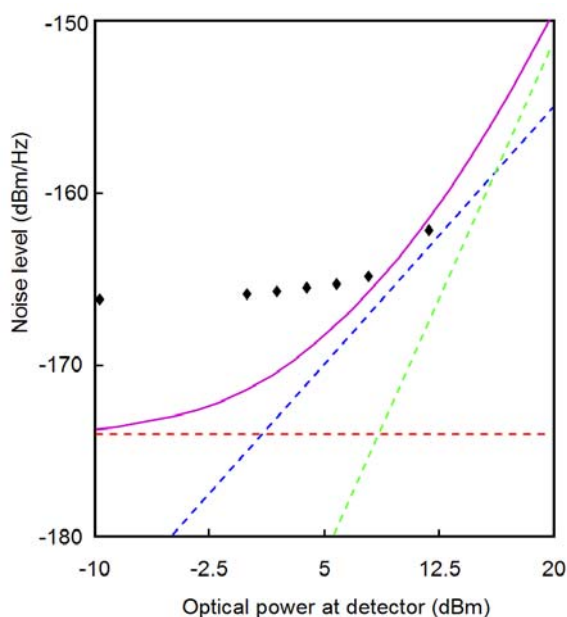


Figure 3 Calculated noise levels in the investigated analog optical link. The three individual noise levels are denoted by the red (thermal noise), blue (shot noise) and green (RIN) curves. The purple line denotes the total noise level. In addition also the data of a noise measurement given (black diamonds).

Using the RF noise and signal levels at the input and the output of the link, the noise figure of the link can be determined. The resulting noise figure levels are given in Figure 4.

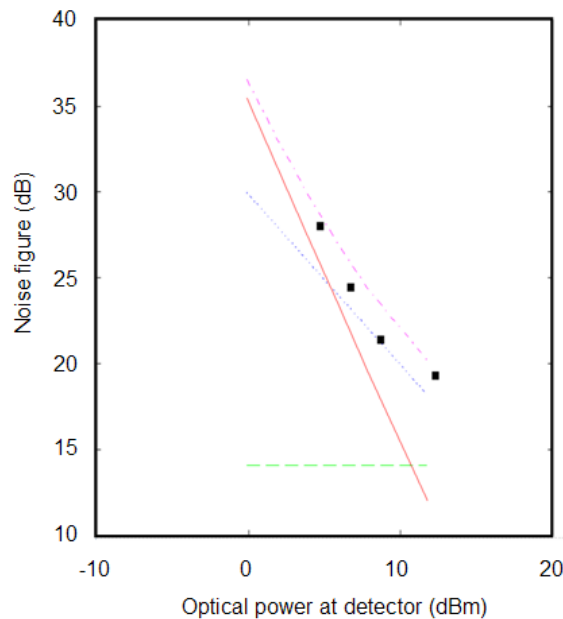


Figure 4 *Calculated (purple) and measured (black) noise figures of the link as functions of the optical power at the detector, for a noise power level at the input of -166 dB/Hz. The calculated NF contributions of RIN (green), shot (blue) and thermal (red) noise are added as well.*

The level of the noise figure is mainly determined by the relatively small link gain that varies from -30 dB at an optical power level of 3 mW, to -15 dB at 17 mW, as shown in Figure 4. All other contributions to the noise figure are related to the three noise sources in the link.

The noise figure of the system can be improved by increasing the optical power in the system, up to the RIN dominated regime, where the NF becomes constant. Further NF reductions beyond this point can only be obtained by a reduction of the RIN of the laser.

3.1.3 Distortion

Distortion in analog (optical) links results from the non-linear transfer characteristic of (one of) its components. In externally modulated analog optical links both the modulator and detector have a non-linear transfer characteristic. Since the non-linear behavior of the modulator is dominant, all analog optical link distortion is ascribed to the modulator. By operating the MZI modulator in its quadrature bias point, the second order distortion is suppressed, leaving only the third order distortion as the main distortion source. The bias level of the modulator is never at its optimal point, due to small drifts in the magnitude of the quadrature bias caused by surface charging effects in the electro-optic actuators of the modulator. As a result a residual second order distortion will always be present. The level of the distortion in the externally modulated analog optical link is experimentally determined, of which the results are given in Figure 5.

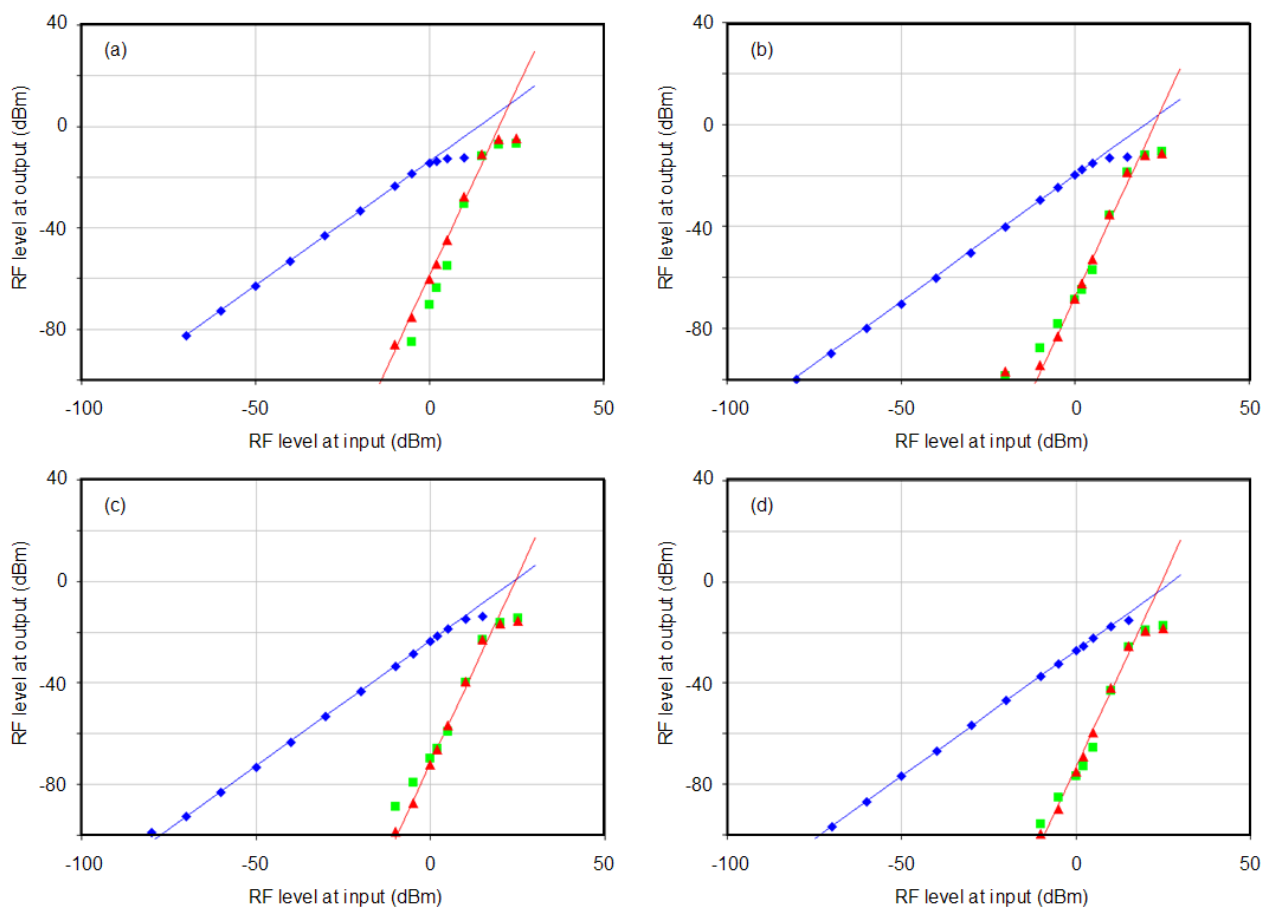


Figure 5 Measured RF signal level (blue) in combination with the second (green) and third (red) order intermodulation distortion levels for four optical output power levels ((a): 12.3 dBm, (b): 8.7 dBm, (c): 6.7 dBm, (d): 4.7 dBm). The blue and red lines are fitted to the signal and third order measurement data.

The intermodulation distortion levels are determined with the use of single tone distortion measurements. The resulting second and third order harmonic distortion levels are used for determining the IM2 and IM3 levels via: $IM2 = HD2 + 6 \text{ dB}$ and $IM3 = HD3 + 9.5 \text{ dB}$.

The measurements show that the residual second order intermodulation distortion has approximately the same level as the third order intermodulation distortion. Based on the IM measurement results given in Figure 5 both the compression point and IP levels are determined and summarized in Table 2.

Table 2 Experimentally determined compression point and IP levels.

Optical power at detector (dBm)	-1 dB compression point (dBm)	-3 dB compression point (dBm)	IIP3 (dBm)	OIP3 (dBm)
4.7	10.3	15.4	23.1	-4.2
6.7	8.3	12.6	24.4	0.9
8.7	6.0	10.1	24.1	4.3
12.3	-0.7	4.0	23.0	8.4

Table 2 shows that the IIP3 is more or less constant. As a result, the OIP3 depends only on the link gain and thus on the optical output power of the link.

3.1.4 Dynamic range

By combining the experimental RF noise level information from Figure 3 and the measurement results of Figure 5, the spur free dynamic range (IMF) of the link can be determined, using [5]:

$$IMF3 = \frac{2}{3} \cdot (OIP3 - P_{\text{noise}}), \quad (2)$$

The results from the measurements are summarized in Table 3, for both small and wide band operation.

Table 3 The calculated IMF3 for both 1 Hz and 1 GHz bandwidths, combined with the input RF level at which the given IMF3 is obtained. The noise level information is retrieved from Figure 3.

Optical power at detector (dBm)	Noise level (dBm/Hz)	1 Hz		1 GHz	
		IMF3 (dB)	RFin (dBm)	IMF3 (dB)	RFin (dBm)
4.7	-168.5	107.49	-31.06	47.49	-10.9
6.7	-166.8	110.68	-31.65	50.68	-11.35
8.7	-164.9	112.52	-32.65	52.52	-12.45
12.3	-160.8	113.22	-34.85	53.22	-14.45

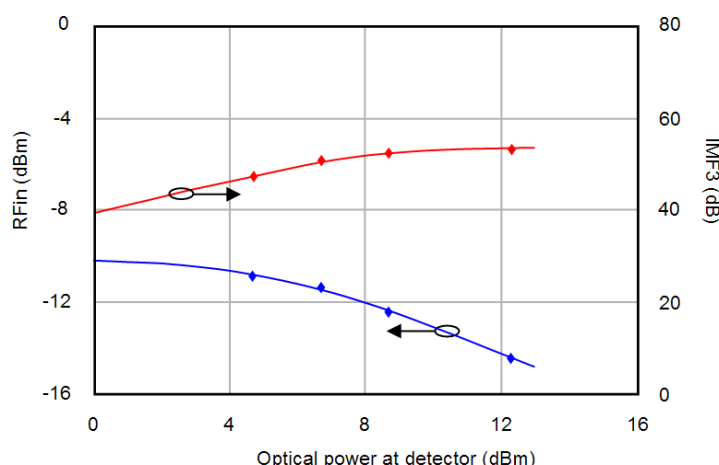


Figure 6 The calculated IMF3 and the accompanying RF input power for a bandwidth of 1 GHz.

Given the linear OIP3 as a function of optical power and the constant noise level at lower optical powers (see Figure 3), the IMF3 at lower optical powers will be linear as a function of the optical power level. At higher optical power levels the signal to noise ratio becomes constant (see Figure 4) resulting in a constant IMF3 at these levels. For the R_{Fin} the opposite situation holds: at lower optical powers it is constant, while at higher optical powers it has a linear dependence on the optical power.

3.2 Direct modulation based links

External modulation systems transfer the electronic signal to the optical domain with the use of a separate modulator. In direct modulation based links the analog electronic signal is placed on an optical carrier by modulating the laser current with the analog electronic signal. The main advantage of this approach is the lower cost level and the reduced system complexity, with respect to the external modulation case.

A number of different laser types are available for direct modulated links. A description of these types is given in Section 2.2.1. The transmission distance of these direct modulation lasers is mostly determined by the optical output power and the dispersion related deterioration of their optical signal in the fiber.

In the external modulation AOL example in the previous section, the focus is on performance and to a lesser extent on cost, the approach in this direct modulation AOL example is the opposite. In the component selection for the direct modulation AOL, the lowest cost components are chosen, as such accepting a somewhat lower component and AOL performance. A description of the components in the direct modulation link is given in Table 4.

Table 4 Direct modulation AOL component properties

Laser		
	Type	Oemarket LDM1550
	Optical power	4 mW
	RIN level	-150 dB/Hz
	Slope Efficiency	0.1 W/A
Detector		
	Type	Oemarket PD-50
	Responsivity	0.8 A/W
	Impedance	50 Ω

3.2.1 Link gain

The link gain level in direct modulated links can be described by Equation (1). In the case of direct modulation both the responsivity and slope efficiency are fixed, device dependent parameters. As a result, the link gain can only be adjusted by applying a different laser and/or detector. The slope efficiency of the laser depends strongly on the type of laser: Fabry-Perot lasers have slope efficiencies in the order of 0.05 W/A, while good DFBs have a slope efficiency of about 0.3 W/A. In combination with a detector responsivity level of 0.9 A/W, link gains of around -10 dB can be realized in direct modulation based links. The link gain can be improved by cascading several lasers. In this way a slope efficiency of 1.01 W/A was obtained for a bandwidth of 5 GHz, with a three-stage InP segmented-ridge cascade laser [14]. An other method for increasing the link gain is to replace the conventional resistive (i.e., lossy) impedance-matching circuits with lossless (at least ideally) reactive impedance-matching circuits. In this way it is possible to completely overcome the electro-optical slope efficiency losses [15].

The bandwidth of direct modulated links is usually determined by the modulation bandwidth of the laser. Around its maximum modulation frequency, the laser starts oscillating. Beyond this frequency, the transfer efficiency declines strongly.

Figure 7 shows the transfer function of a direct modulated AOL as a function of the modulation frequency for a number of bias levels. It shows that beyond a bias level of 15 mA, a proper link operation is obtained. The laser oscillation around 8 GHz can clearly be seen. The non-flat characteristic below the oscillation frequency is caused by an imperfect impedance matching between the rf source and the laser. By applying a more optimized matching circuit a flat response up to the oscillation frequency is obtained.

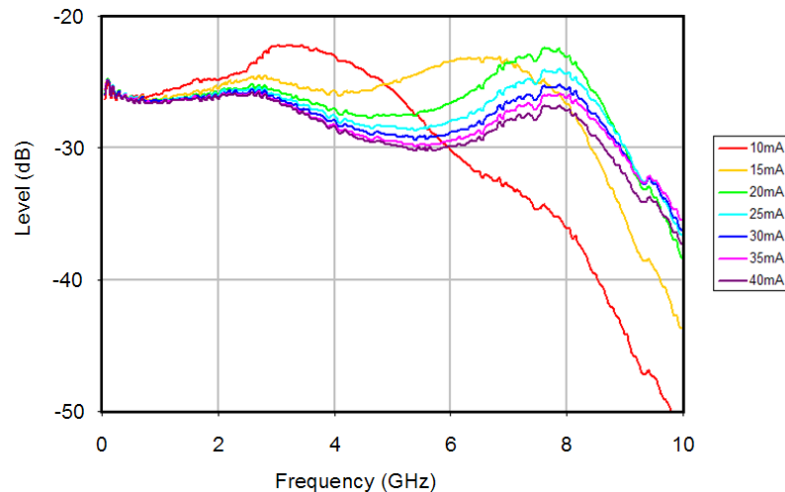


Figure 7 *The measured transfer function of a direct modulated AOL as a function of the modulation frequency, for a number of bias levels, using an Agere R2560A detector and a RF input power of 0 dBm.*

Currently direct modulated lasers with modulation bandwidths up to 40 GHz are available. For obtaining these high bandwidths special techniques are required. Regular COTS DMLs operate at frequencies up to 10 - 15 GHz.

3.2.2 Noise

Within direct modulation links the same noise sources are present as in externally modulated systems. As such the description of the various noise sources given in Section 3.1.2 also holds for direct modulated links. Within a direct modulation system the level of the three noise contributions depends, like in the external modulation case, on the output power level of the laser (i.e. on the optical power level at the detector). The situation described by Figure 3 gives a good idea of the relative positions of the noise levels: at low optical power levels the detector thermal noise is dominant, while at higher optical power levels the RIN noise level is the highest.

The main difference between direct and external modulated links is their link gain dependence on the optical power level. In external modulated links the link gain depends quadratically on the optical power level, while in direct modulated links this gain is constant as function of the optical power level, due to the straight LI-curve of a laser.

In case the optical power level at the detector is adjusted by changes in the optical losses in the fiber, the link gain behaves like in the external modulation situation. The calculated noise level and NF as functions of the optical power at the detector for this case are given in Figure 8.

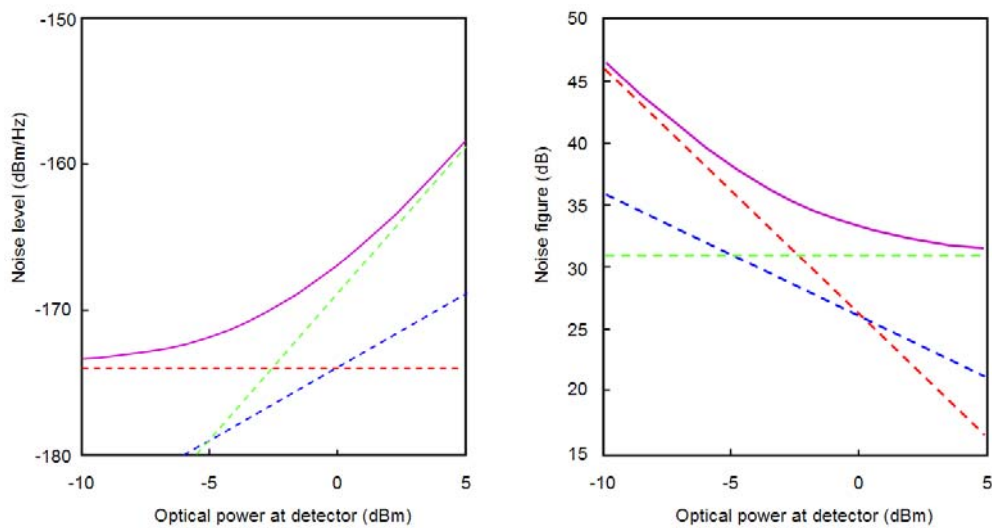


Figure 8 Calculated noise level and noise figure (purple) of the direct modulation link as functions of the optical power at the detector, for a noise power level at the input of -166 dB/Hz. The calculated contributions of RIN (green), shot (blue) and thermal (red) noise are added as well.

At low optical losses in the fiber the NF of the AOL is 32 dB.

3.2.3 Distortion

Within direct modulated AOLs both the laser and the detector introduce distortion in the system. Usually the laser related distortion is dominant. The level of the distortion spurs does not only depend, like for the external modulator case, on the RF power, but also average optical power and frequency strongly influence the level of the spurs. Since the design and layout of the laser strongly influence its distortion properties as well, it is hard to make quantitative statements about the distortion levels in direct modulation links. The lowest distortion levels are provided by DFB lasers. High performance DFBs have IIP2 levels up to 60 dBm and IIP3 levels up to 35 dBm. The distortion levels of a lower cost DFB type are depicted in Figure 9.

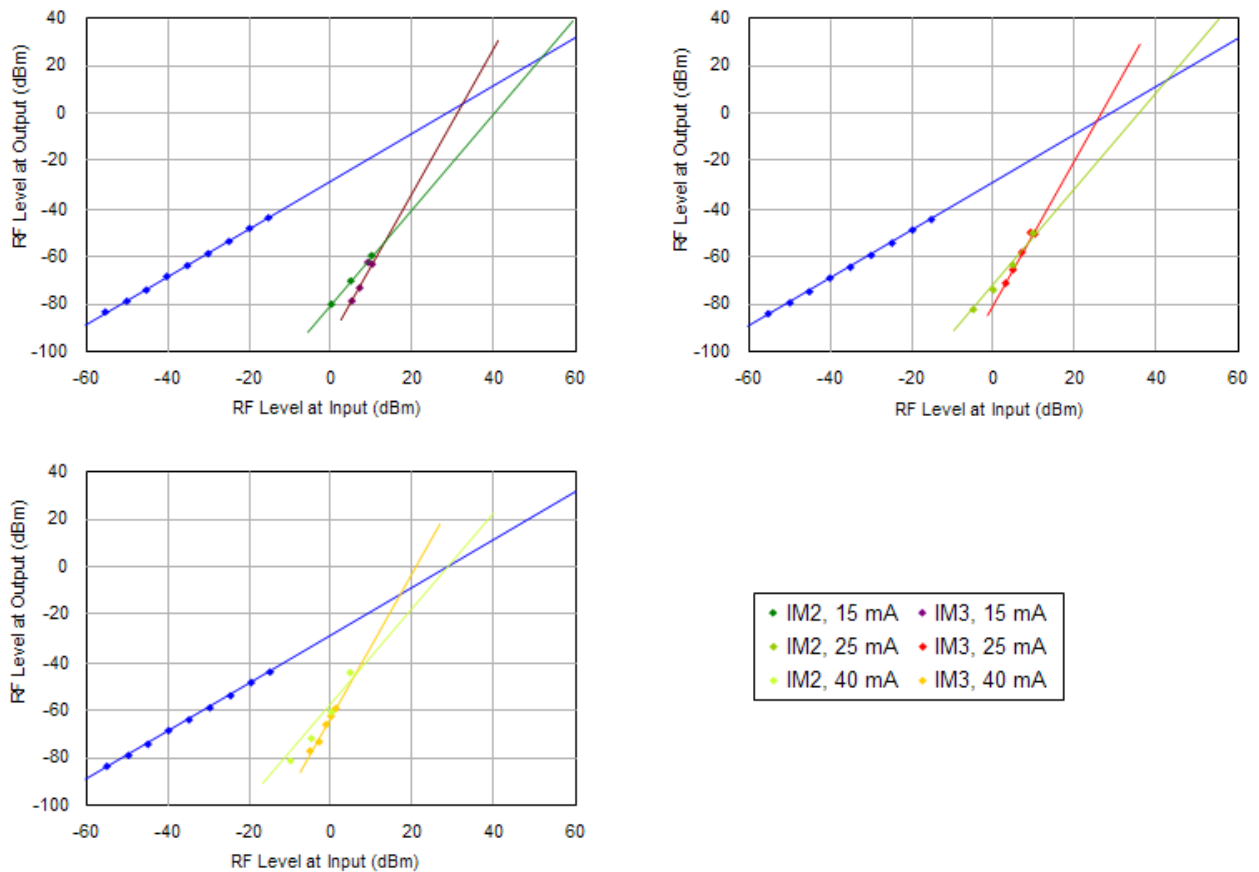


Figure 9 The measured second and third order intermodulation distortion and RF power at the output of the link as functions of the RF input power for three laser current bias levels at a signal frequency of 1006 MHz.

The measurement results in Figure 9 show the dependence of the second and third order harmonic distortion on the laser bias level: the lower the bias level, the lower the harmonic distortion levels at the output of the link. Since bias levels below 15 mA will limit the bandwidth of the laser (see Figure 7), a bias of 15 mA is needed for lowest link distortion. In this, it should be noted that the distortion also depends on both the optical power level [16] and the modulation frequency [17].

From the measurement results depicted in Figure 9 an IIP2 level of 52 dBm and an IIP3 level of 33 dBm is determined.

3.2.4 Dynamic range

The dynamic range of direct modulation based AOLs can be determined using Equation (2). By using $OIP3 = 6$ dBm, $OIP2 = 25$ dBm and $P_{noise} = -158$ dBm/Hz, a second and third order dynamic range of approximately 47 dB and 49 dB are obtained for a bandwidth of 1 GHz.

3.3 Transmission distance

Every AOL transmission distance has a specific AOL type. The (maximum) transmission distances of these AOL types is mostly determined by the type of transmitter in the AOL. For satisfying the most stringent requirements on the transmission distance, external modulation based AOLs will be needed. For the short and intermediate range AOLs, direct modulation will provide sufficient performance.

In the case of direct modulation a number of transmitter types can be distinguished. For short range applications (10s of meters), low cost multimode transmitters, whose transmission distance is limited by modal dispersion, are suitable. For somewhat longer distances (~100 m) single mode FP lasers, with a chromatic dispersion limited transmission distance, are a good option. For the longest distances single mode DFBs/DBRs are available, whose transmission distances are only limited by their optical output power level. In case high performance links are needed, DFB/DBR based links are most suitable.

In the following subsections the different causes of the AOL transmission distance limitation are described.

3.3.1 The influence of optical power on the AOL transmission distance

One of the most important transmission distance limitation is related to the limited amount of optical power in the AOL. By increasing the length of the AOL the optical power at the detector will be reduced, causing a link gain reduction and a change in the shot noise level and resulting in an NF increase and a reduction of the dynamic range of the link. The impact of a AOL length increase depends on the length of the link, the type of link and the type of components in the link. In Section 4.2 a more detailed description of this will be provided.

In addition to optical power related transmission distance limitation, also dispersion and fiber non-linearity related distortions will influence the maximum transmission distance. Both will be treated below.

3.3.2 The influence of dispersion on the AOL transmission distance.

3.3.2.1 Modal dispersion

Two optical output types are used for AOL lasers: a multimode output and a single mode output. In case of the first, the optical field in the laser pigtail is relatively large (~50 μm), while the single mode version has an optical field diameter at its output of just 9 μm . In the multimode fiber of the first laser type, a multiple amount of optical modes are present each of which is excited by the laser.

Due to modal dispersion the transmission distance of this type of link is limited [1] with respect to transmission distance and frequency/bandwidth to about 1000 meter at 1 GHz.

Thanks to the relatively large optical field, the fiber-chip alignment is relatively easy and thus low cost, which makes the application of multimode components attractive in many cases.

3.3.2.2 Chromatic dispersion

Due to chromatic dispersion in the fiber, dispersion related signal deterioration occurs. The deterioration characteristics depend on the type of laser and the modulation type. The chromatic dispersion in a link can be compensated by e.g. applying additional fiber with opposite dispersion or SOAs [18].

CSE and coherence effect

A number of effects contribute to signal degradation: the most important is the carrier fading or suppression effect (CSE) that is present in both single and multimode laser systems. CSE is related to the dispersion related phase offset between the upper and lower modulation sidebands. A second, smaller, effect is the coherence effect which causes a signal deterioration due to the nonzero linewidth of the laser. Both effects will lead to deterioration of the transfer function of the link and an increase of the nonlinearity levels. The CSE can be removed from external modulation based AOLs by applying single sideband modulators.

The influence of CSE on the transmission distance is depicted in Figure 10, which shows the calculated signal level as a function of both modulation frequency and distance.

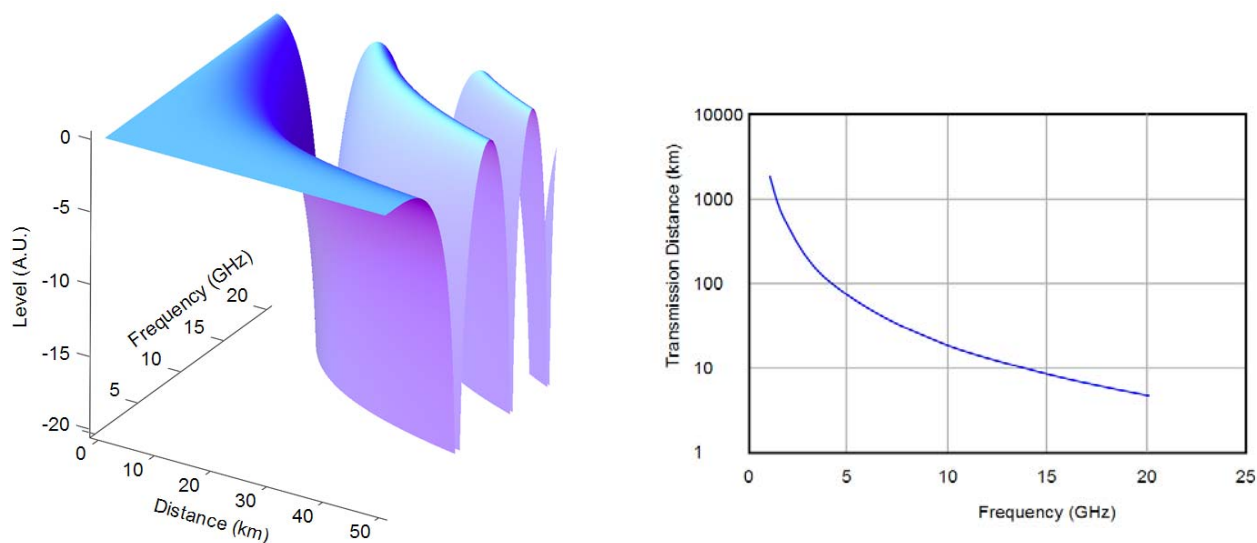


Figure 10 Signal deterioration by CSE: calculated signal level as a function of frequency and transmission distance (left) and the CSE limited transmission distance at -3 dB level as a function of the signal frequency (right).

Longitudinal mode dispersion

In links with Fabry – Perot lasers a strong signal deterioration occurs due to the transversal filtering effect in which the signal quality degrades due to different propagation delays of the FP longitudinal modes [2]. The longitudinal mode dispersion will limit the transmission distance of a 1 GHz signal to ~ 2 km. At higher (lower) frequencies the transmission distance will be shorter (longer).

Chirp related dispersion

When lasers are directly modulated, a small shift in the carrier wavelength can be observed. This so called chirp in combination with the chromatic dispersion in the fiber will deteriorate the signal at the detector and will reduce the maximum transmission distance, when compared to the external modulation case. Since every laser and modulation format has its own specific chirp. The chirp related transmission distance limitation need to be determined for every AOL type.

3.3.3 The influence of fiber non-linearities on the AOL transmission distance

The refractive index of silica, the major material of optical fiber, has a slight dependence on the intensity of the optical field, which is known as the optical Kerr effect, which introduces a number of non-linear effects in the fiber. Non-linear effects must be taken into account in case higher optical power levels are employed and become even more important in case wavelength division multiplexing is applied. Non-linearities can already occur at reasonable powers of few dBm in the fiber in the case of large transmission distances. A number of non-linear effects can be distinguished:

- *Self-phase modulation (SPM)*: self-induced phase shift experienced by an optical field during its propagation through a fiber.
- *Modulation instability (MI)*: spontaneous modulation of the light in a fiber.
- *Cross phase modulation (XPM)*: in case multiple optical WDM channels propagate inside the fiber, the refractive index seen by a particular wave does not only depend on the intensity of that wave but also on the intensity of other copropagating waves.

- *Four-wave mixing (FWM)*: a number of wavelengths propagate together through an optical fiber. Providing a condition known as phase matching is satisfied, light is generated at new frequencies using optical power from the original signals.

All four contribute to the total signal distortion in a different way and with a different strength. SPM, MI and XPM will cause an increase of the (phase / intensity) noise level, while FWM will introduce (additional) spurs. The influence of these non-linearities depends strongly on the AOL configuration and needs to be determined for every individual optical link.

4 Implementation of analog photonic links in astronomy instrumentation

The applicability of AOL technology in radio-astronomy instrumentation depends on the requirements of the possible AOL application areas and the performance of AOL technology when applied in these RF (sub)systems. In this chapter both items treated.

In the AOL/RF system calculations two types of AOL technology are used as an example. The first example system uses external modulation. In the selection of the components the focus is on link performance and to a lesser extent on cost. For the second example AOL system, which is based on direct modulation, an opposite approach is used.

4.1 Application areas of AOL technology in astronomy systems

In finding the proper application areas of AOL technology, it is important to determine those system sections where the advantage of AOL, broadband performance with a long transmission distance, is needed.

Since AOLs deal with *analog* signal transfer, the AOL application areas will be in the system front-end. Taking into account the cost level and AOL performance the following application areas of AOL technology in the SKA front-end can be distinguished:

- (1) *Signal transfer from aperture array tile to aperture array station signal-processor*
Aperture array tiles will process signals with frequencies up to ~ 1 GHz. Multiple tile system architectures are being investigated, ranging from all-analog to all-digital. Only for the first, analog signal transfer between the tile and the (station) signal processor is needed. In this case, AOL technology does only provide a competitive alternative, with respect to coax based signal transfer, in case a relatively long transmission distance ($> \sim 100$ m) is needed.
In the order of 10 links per tile to signal processor connection will be needed in case every tile beam is to be transferred individually to the station signal processor.
- (2) *Signal transfer from single pixel feed to dish station signal processor*
In single pixel feed systems the operational frequency band will go from ~ 1 GHz up to 10 - 15 GHz. AOL technology is very suitable for the analog transfer of the signals in this broad frequency band. The transmission distance depends on the final system configuration and will be in the order of several hundreds of meters up to several kilometers. A part of the link will run along the mechanical construction of the dish, where it will be exposed to different weather types. The cable needs to be flexible such that it can deal with the movements of the dish.
- (3) *Signal transfer from phased array feed to PAF-dish (station) signal processor*
The situation described in the previous item also holds for the PAF-dish signal transfer system. However, instead of just employing a single link, a PAF system needs multiple links from the focal plane of the dish to the signal processor. In case the signal from every feed needs to be transferred individually to the signal processor, in the order of hundred links are needed in case of a dual pol 8x8 PAF system.

4.2 RF systems with AOL technology: an example with external modulation based AOL

4.2.1 RF link configuration

In this section a receive antenna remoting RF system with AOL is treated. Information about the optical components in this example system is given in Table 1.

In most analog electronic system designs, RF amplifiers are applied at the in and output of the AOL. In this way the proper signal powers are applied to the AOL and the system behind the AOL. In case of a antenna remoting system, the antennas are placed to the AOL as close as possible. Only a RF amplifier system is placed in between for obtaining proper RF link properties and RF power level at the input of the AOL link. The scheme of the example RF system is given in Figure 11.

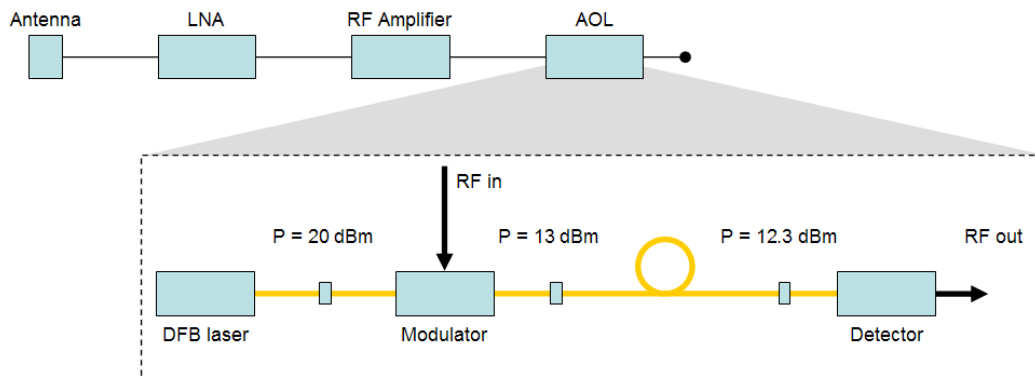


Figure 11 The configuration of the example RF system and the accompanying AOL.

RF amplifier system consists of a LNA and a regular RF amplifier. The performance of the components in the RF system are given in Table 4.

4.2.2 Analog optical link: RF parameters

The RF performance of the AOL can be determined with the use of the information in Section 3.1. In determining the magnitude of the relevant parameters, the link configuration depicted in Figure 11 is used. In the example link an optical power level at the detector of 12.3 dBm is used.

Noise Figure

The noise figure is determined with the use of Figure 4. Within the example system an optical power level of 12.3 dBm is present at the detector. At this level a NF of 19 dB is determined.

RF gain

With the use of Figure 2 the RF gain at an optical power level of 12.3 dBm is determined to be -14.6 dB.

IP2 and IP3

Since the modulator in the analog optical link is operated in its quadrature point, theoretically the IP2 level in the optical link is infinite. Due to instabilities in the modulator, the actual IP2 level is much lower, but still exceeding the IP3 level in the link. Therefore, second order distortion will not be taken into account in the analog optical link calculations. The IIP3 of the link is assumed to be approximately 23 dBm at every optical power level. The OIP3 can be determined by multiplying the IIP3 with the link gain.

In addition to the above mentioned parameters, additional information about the analog optical link can be retrieved from the analog optical link measurements and calculations. The following additional items can be specified for a optical output power level of 12.3 dBm:

- -1 dB compression point: -0.7 dBm, assuming a linear behavior as function of the optical power.
- IMF3: 53 dB, see Subsection 3.1.4.
- RFin -14 dBm, see Subsection 3.1.4.

The performance of the components in the RF system is given in Table 4.

Table 5 The RF performance of the components in the RF signal path of the example system

	Type	Gain	NF	IP2		IP3	
				In	Out	In	Out
				(dBm)	(dBm)	(dBm)	(dBm)
Antenna		-0,2					
Low Noise Amplifier	ATF-54143	16	1.5			18.0	36
RF Amplifier	MGA-53543	20	3.3			22	33
AOL		-14.6	19			23	8.4

4.2.3 RF system performance calculations

In this section the gain, noise figure, distortion and SFDR of the RF system, as depicted in Figure 11, are determined. In parallel, the influence of the AOL on the total RF system performance is described. The calculations below can be used as an example for future RF system/AOL calculations.

RF system Gain

In Subsection 3.1.4 the RF input power level is determined to be -14 dBm. The gains in the RF system should be such that the maximum RF power level in the receiver system does not exceed this -14 dBm level. According to the ASTRON experience the maximum RF output power level of a (Vivaldi type) radiator in a phased array receiver system is -50 dBm. To obtain the proper power level at the input of the optical link, the gain of the RF amplifier is set to 20 dB.

RF system Noise Figure

The noise figure of the system is determined with the use of the gain, input and output noise power via,

$$NF = \frac{N_{out}}{G \cdot N_{in}} \quad (3)$$

Via the NF information given in Table 4 the noise power generated in a component (N_{add}) can be calculated with the use of:

$$NF = \frac{N_{add}}{G \cdot N_{in}} + 1, \quad (4)$$

under the assumption that the noise figures of the various components are given with respect to a standard noise source with noise power kTB . With all this information and the use of an antenna temperature of 80 K the noise powers generated by the various components and the noise figure of the system up to the component is calculated. The results for a bandwidth of 1 GHz are given in Table 5. The noise figure is calculated for the system between the antenna and the specified component and is calculated with respect to the input noise power from the antenna.

Table 6 The calculated noise power contributions of the components and the noise figures at the output of a number of components in the RF signal path of the example system for a bandwidth of 1 GHz.

	Noise Power	NF
	(dBm)	
Antenna	-89,6	
Low Noise Amplifier	-71.8	2.5
RF Amplifier	-63.4	2.6
Optical Link	-69.6	2.5

The information in Table 5 shows that in spite of the relatively high NF of the AOL subsystem, a low total system NF is obtained.

Up to now only a short link length situation is taken into account. To see the influence of a longer link length on the system NF, additional optical loss should be taken into account. In the case of the example system a 1550 nm DFB is used, at which wavelength an fiber attenuation of 0.25 dB/km is present. This fiber based loss will result in a reduction of the link gain, which is equal to twice the optical attenuation in dB (i.e. link gain reduction of 0.5 dB/km), according to Equation (1). Figure 12 shows that for link lengths up to 10 km (Pop > 10 dBm), no changes can be observed in the system NF.

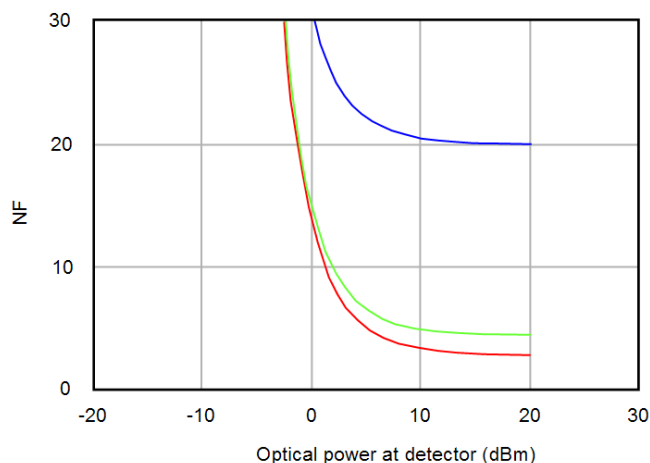


Figure 12 The calculated RF system noise figure as a function of the optical power at the detector. The different colors represent different RIN levels in the source laser; red: -170 dB/Hz, green -160 dB/Hz, blue: -150 dB/Hz.

For optical power levels below 10 dBm, the RF system NF is limited by the AOL noise. At these lower optical detector powers, the increase in NF is mainly caused by the strong link gain reduction in combination with the constant thermal noise power from the AOL.

Figure 12 also shows that the laser noise level is sufficiently low, not to limit the RF system NF. Even a RIN level degradation from -170 dB/Hz to -160 dB/Hz would be acceptable.

High optical power levels at the detector are not only favorable for the noise figure, also the dynamic range improves at elevated optical levels at the detector (see Figure 6).

IP2 and IP3

In the RF signal paths of the photonic receiver system a number of RF components are connected in cascade. The IP2 and IP3 levels in each of these signal paths must be determined by amplitude addition of the individual intermodulation spurs [7].

However, since the gain and IP levels of the two RF amplifiers in the signal paths are relatively high, their contribution to the distortion signal at the output of the system can be neglected. As a result, the IIP3 of the RF signal path can be expressed as:

$$IIP3_{\text{link}} = IIP3_{\text{OAL}} - \text{Gain}_{\text{LNA}} - \text{Gain}_{\text{Amp}}, \quad (5)$$

resulting in an IIP3 level for the example RF system of -13 dBm and an OIP3 level of -27.6 dBm.

IMF3

With the use of Equation (2) the IMF3 of the RF system is calculated. The results are given in Figure 13. The figure shows an IMF3 level of about 48 dB for optical powers at the detector beyond 10 dBm and a laser RIN of -170 dB/Hz.

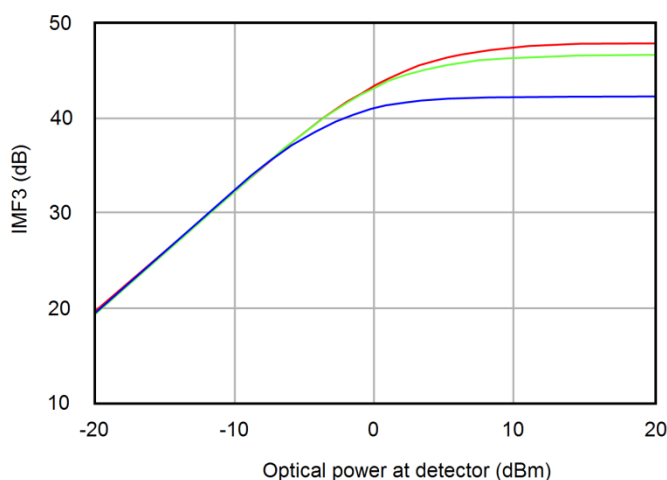


Figure 13 The calculated IMF3 of the RF system as a function of the optical power at the AOL detector. The different colors represent different RIN levels in the AOL source laser; red: -170 dB/Hz, green -160 dB/Hz, blue: -150 dB/Hz.

The IMF3 limitation above detector powers of 0 dBm is explained by Figure 14, in which the contributions of the various noise sources are given.

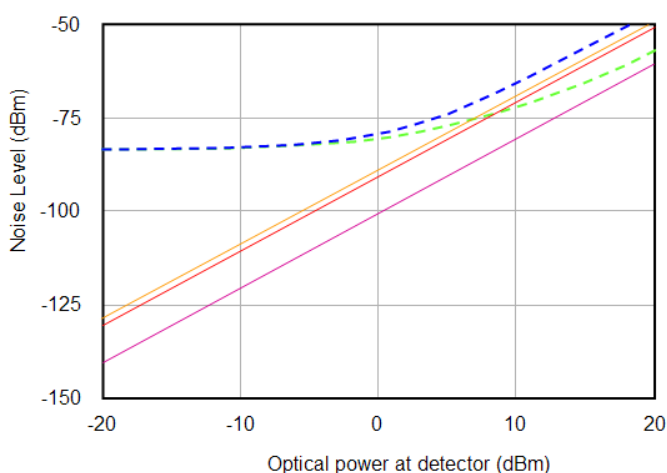


Figure 14 The calculated noise levels after the AOL in the RF system as a function of the optical power at the AOL detector. The different colors represent different noise contributions; blue: total noise level, green: AOL with RIN level of -170 dB/Hz, orange: LNA, red: antenna, purple: Amp.

The figure shows for optical power levels beyond 5 dBm the noise of the antenna and LNA become dominant. Since these noise levels and the AOL gain depend similarly on the optical detector power, the IMF3 becomes constant as a function of the optical power. The high antenna and LNA noise levels at the output of the link are caused by the relative high RF amplification in front of the AOL. By increasing the optical power at the detector, the RF input power level can be reduced (see Figure 6), resulting in a reduction of the required RF gain, which in its turn causes a reduction of the LNA and antenna noise levels.

Further improvements need to come from further optical loss reductions, a reduction of the RIN level and an increase of the IIP3 of the AOL, although this latter approach will cause an increase of the RF AOL input

power resulting in an increase of the required amplification in front of the AOL and thus an increase of the noise level.

4.3 RF link performance: analog electronic systems with direct modulation

In the case of a direct modulation AOL, only a laser and detector are needed in the optical link. A short description of both is given in Table 4. The configuration of the direct modulation example AOL is given in Figure 15. It shows two modulators in front of the AOL whose amplification level can be adjusted to the needs of the direct modulation AOL. The amount of amplification that is needed is determined by the noise level and the levels of the distortion spurs.

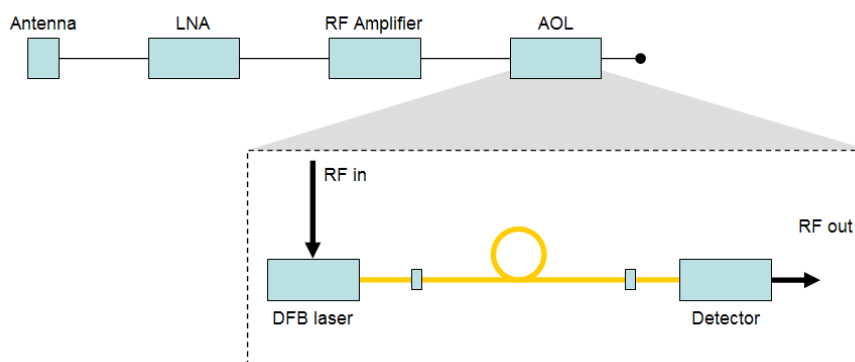


Figure 15 The configuration of the example RF system and the accompanying direct modulation AOL.

In the link a widely available, low cost 10 mW DFB is applied. In Table 7 the RF properties of the different components in the RF system with direct modulation AOL are given. The information about the AOL is obtained from Section 3.2, assuming an (optimal) laser bias level of 15 mA.

Table 7 The RF performance of the components in the RF system with direct modulation AOL.

	Type	Gain	NF	IP2		IP3	
				In	Out	In	Out
				(dBm)	(dBm)	(dBm)	(dBm)
Antenna		-0,2					
Low Noise Amplifier	ATF-54143	22	1.5	18		18	
AOL		-27	32	52	25	33	6

In addition to the information in Table 7 also the IMF2, IMF3 and RFin levels of the AOL can be determined.

- IMF2 (AOL): 47 dB
- IMF3 (AOL): 49 dB
- RFin (AOL) -28 dBm

With the use of this AOL and RF component information and the calculation approach that is described in Section 4.2.3, the NF, dynamic range and transmission distance are determined.

Noise Figure of the RF system

The calculated NF as a function of the optical power at the detector for a 1 GHz bandwidth is given in Figure 16. For the DM AOL with a laser with a RIN level of -150 dB/Hz, a large RF system NF is obtained, even with no optical loss in the fibre.

This high system NF is caused by:

- *The relatively low RF gain in front of the DM AOL*
A calculation shows that at least 35 dB of RF gain in front of the AOL is needed to realise a NF < 5. At this gain level the dynamic range will be IP2 limited and will be less than the maximum obtainable dynamic range
- *The relatively high RIN noise*
- *The relatively low link gain*

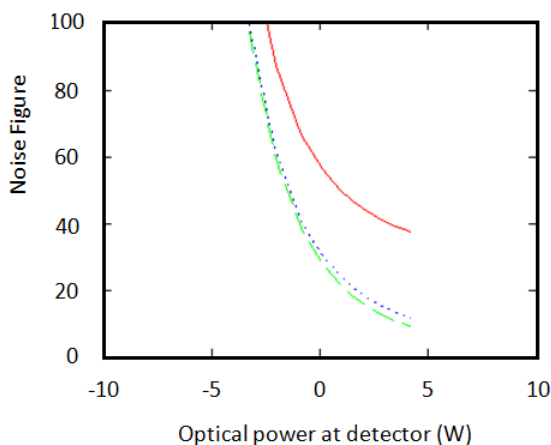


Figure 16 The calculated Noise Figure of the RF system as a function of the optical power at the AOL detector for a frequency band of 1 GHz. The different colors represent different RIN levels in the AOL source laser; red: -170 dB/Hz, green -160 dB/Hz, blue: -150 dB/Hz

Dynamic range of the RF system

With the use of the information about the noise, link gain and distortion levels the second and third order intermodulation free dynamic range is calculated. For a RIN level of -150 dB/Hz and no attenuation in the optical fibre, an (LNA limited) IMF2 of 46 dB and an (AOL limited) IMF3 of 56 dB are calculated for a frequency band of 1 GHz. The calculation results are given in .

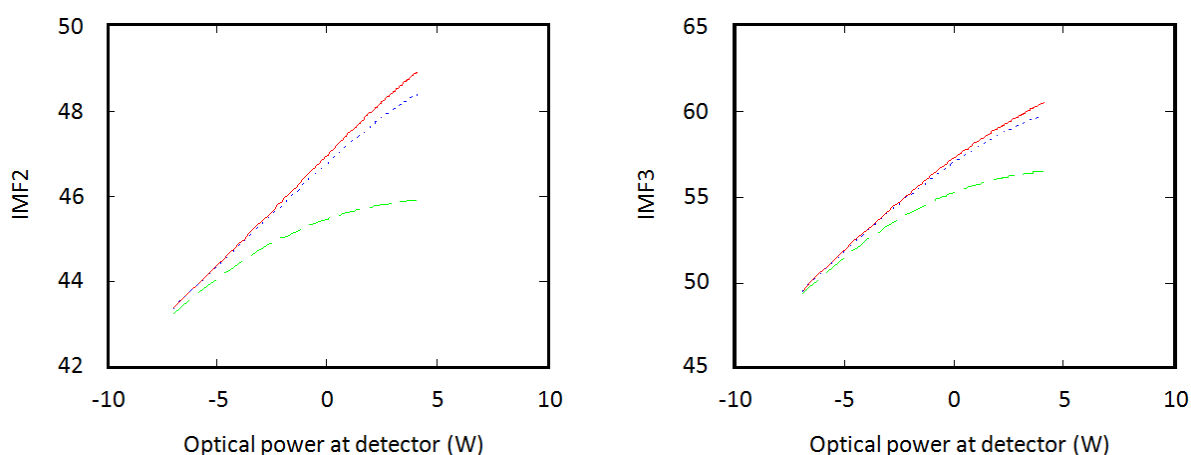


Figure 1 The calculated IMF2 and IMF3 of the RF system as a function of the optical power at the AOL detector for a frequency band of 1 GHz. The different colors represent different RIN levels in the AOL source laser; red: -170 dB/Hz, green -160 dB/Hz, blue: -150 dB/Hz

5 Analog optical link costs

In this chapter the cost level of the three most important optical AOL components are discussed. The costs of the driver electronics for these components is in the order of ~ 1 Euro per component in case a custom made solution is used. This level is relative low when compared to the costs of the optical components.

5.1 Lasers

The cost level of the AOL components depends strongly on their performance. Small bandwidth (< 5 GHz) lasers are usually low cost (~ 100 Euro), while beyond 5 - 10 GHz the cost increase strongly towards a 1000 Euro level. For lasers also the type of laser and the package type are important. VCSELs and FP lasers in co-axial or TOSA packages are low cost components with a pricing level in the order of about 100 Euro for ~ 5 GHz modules, while the pricing of broadband (TEC cooled), high optical power DFBs in a butterfly package can go beyond 1000 Euro.

The cost level of components also strongly depends on the size of its commercial market. For < 1 GHz, multimode FP lasers and VCSELs a big market is present resulting in a pricing below 100 Euro, while specialty products like e.g. a balanced receiver (u2t Photonics or Discovery Semiconductors) cost about 10kEuro.

In the two example systems two laser types are used. In the external modulation AOL a high power CW DFB is used. The direct modulation link employs a low cost direct modulation DFB laser. A cost inventory for both types is given below.

5.1.1 High power DFB laser inventory

The COTS high power DFB lasers that are available nowadays were inventoried and are summed up in Table 8.

Table 8 Information about commercially available high power DFB lasers.

Supplier	Component ID	P _{opt,max} (mW)	RIN (dB/Hz)	λ (nm)	Linewidth (MHz)	Costs		Amount	Comment
						Euro	US Dollar		
Oclaro	LC95A76ULR	250		976	4500				CIP gets its DFBs from EM4
CIP	DFB-080-XXX	80	-150	1550	1				
EM4 Inc.	EM253	100 - 120	-170	1550	1	974 1227	1550 1950	64 <10	
Ortel / Emcore	1772-NM-63-02-FC-PM	63	-163	1550	1	1485		64	
Lumics	LU1064M150	150		1064	30				
Toptica	DFB	60		1550	5				Reseller of these components
Toptica	DFB	140		970	5				

Since the 1550 nm window provides the lowest optical loss in the fiber, 1550 nm components are favored. The inventory showed that only two suitable DFBs are available in the 1550 nm window: EM4 and Ortel DFBs. Since the EM4 laser has the highest output power, this type is preferred.

5.1.2 Low cost, direct modulation DFB laser inventory

A wide range of manufacturers and resellers offer a big amount of direct modulation laser types. A growing amount of these laser components are being fabricated in China, resulting a (strong) reduction of the price level. In the inventory most attention was paid to resellers that are willing to sell only limited amounts (hundreds) of laser components. The larger companies are only interested in selling large quantities of laser components and thus less interested in our activity. Information about a number of suitable DFB lasers is given in Table 9.

Table 9 Information about commercially available direct modulation DFB lasers.

Supplier	Component ID	P _{opt, max} (mW)	RIN (dB/Hz)	λ (nm)	Bandwidth (GHz)	Costs		Amount	Comment
						Euro	US Dollar		
OEQuest	LDM5S515-005	2	-150	1550	2.5		125		
OEmarket	LDM1550	4	-150	1550	2		199		Measured bandwidth 9 GHz CWDM laser
	LDM-C	3	-150	CWDM grid	2.5		239		

5.2 Modulators

Both Mach-Zehnder Interferometer (MZI) and Electro-Absorption (EA) modulators are available for the modulation frequencies that are needed by the astronomy instrumentation (up to ~15 GHz). MZI type modulators are preferred thanks to their higher maximum optical input power level. The phased array systems in astronomy instrumentation require a large dynamic range. This large dynamic range is obtained in optical analog links by using:

- large link gains
- low noise levels
- large IP2 and IP3 levels

In addition to need for large link gains for obtaining the proper dynamic range, a proper link gain is also needed to reduce the amount of (RF) amplification that is needed in the signal path, and thus the component costs. Both the link gain and the IP2/IP3 levels in the link are (partly) determined by the modulator. Apart from the (50Ω resistor) thermal noise, the modulator does not contribute to the noise in the link.

In Table 10 information is given about commercially available MZI modulators. In the table a number of component parameters are given. Also the (calculated) linkgain that can be obtained is given. In this calculation the following assumptions are used:

- P_{laser} : optical output power of the laser, is set to the maximum optical input power of the modulator
- r_d : responsivity of the detector, is set to 0.85 A/W
- Loss_{fiber} : optical loss in the fiber, in the calculations loss is not taken into account (i.e. set to 1)
- R_{..} : resistor, is set to the standard value of 50 Ohms.

Table 10 Information about commercially available MZI intensity modulators.

Supplier	Component ID	V π		Pop-in		Prf-in		Δv (GHz)	IL (dB)	Wavelength (nm)	LinkGain (dB)
		(V)	@ v	(dBm)	(mW)	(dBm)	(mW)				
Photline	MXAN-LN-10	5.1	50kHz	23	200	28	631	12	4 dB	1480 - 1600	0,4
	NIR-MX-LN	4.0	50kHz	20	100	28	631	12	5.0 dB	980 - 1064	-5,5
JDSU	APE Microwave Analog Intensity Modulator	6.0	1 GHz		200	27	500	9	5.0 dB	1540 - 1560	-3
	2.5 Gbps bias free Miniaturized Modulator	3.7	100 kHz		100*	24	250	3	5.0 dB	1535 - 1565	-4,8
	2.5 Gbps Bias-free Modulator w. Attenuator	3.7	100 kHz		100*	24	250	3	6.5 dB	1535 - 1565	-7,8
Crisel Instruments	Standard, 1550nm, 18GHz	5.0	1 kHz		300		300	20	5.0 dB	1530 - 1570	2,1
	Standard, 1060nm, high extinction ratio	4.1	1 kHz		100		300	5	4.5 dB	1040 - 1070	-4,7
	Linearised modulator	5.5	1 kHz		100*			20	7 dB	1530 - 1570	-12,3
	Custom AM1550	3.5	2 GHz		150			2	4	1550	
EOSpace	10-20 Gb/s Z-cut Modulator	3	1 GHz		100*			12.5	3 dB	1550	0.9
	10-20 Gb/s X-cut Modulator	4	1 GHz		100*			12.5	4 dB	1550	-3,5
Sumitomo	2.5Gbps Bias Free IM	4.5	2 Gb/s		20				5.5 dB	1530 - 1570	-21,5
Covega	LN058	3.5	20GHz		100*				5.5 dB	1525 - 1605	-5,3
Avanex	PowerLog FA-20	4	1 kHz		100	28		12	3.5 dB	1525 - 1615*	-2,5
	PowerLog AM-20	5	1 kHz		100	25		20	4.5 dB	1525 - 1615 *	-6,4
Lumera	20Gbps polymer IM	1.1	3 kHz		100*			16	11 dB	1528 - 1610	-6,3
SWT	MOD22212	5			100*			8	5.0 dB	1525 - 1605	-7,4
Fujitsu	12 Gbps External Modulator	3	9 GHz		100*			9	5.0 dB	1530 - 1610	-3,4
Srico											
Versawave	40 Gb/s Amplitude Modulator	3.5 V	40 Gb/s		100*			40	3.5 dB	1530 - 1610	

* assumed value

NOTE:
3 dB
additional
loss at
quadrature

* also
@1310nm

In Table 10 info the most attractive items are highlighted in green.

When looking at the link gain, the following components are the most attractive:

- Photline / MXAN – LN-10
- JDSU / APE Analog IM
- Crisel / Standard 18GHz
- EOSpace / 10-20 Gb/s Z-cut Modulator
- Avanex / Powerlog FA-20

In Table 11 the results of a quotation request for these components are given.

Table 11 Cost info for the selected COTS MZI intensity modulators.

Supplier	Component ID	Cost / item		Comment
		Euro	Dollar	
Photline	MXAN-LN-10	1680		
JDSU	APE Analog IM	2615		
Crisel Instruments	Custom AM 1550nm 3GHz	3750		
EOSpace	10-20 Gb/s Z-cut Modulator	-		
Avanex	PowerLog FA-20	-		

The Photline modulator is selected as the most attractive modulator.

5.3 Detectors

The most important technical criterion in selecting a modulator is its responsivity level, which needs to be as close to 1 as possible. Also bandwidth and maximum optical input power are important when selecting a detector. The non-linearity of detectors is for almost all detectors very small and can be assumed to be in-line with the system requirements.

The market situation for detector components shows much resemblance with the earlier described laser market. At lower frequencies (< 3 GHz) the costs are low, while at higher frequencies the cost level increases.

Table 12 Information about commercially available detectors.

Supplier	Component ID	P _{opt, max} (mW)	Responsivity (A/W)	λ (nm)	Bandwidth (GHz)	Costs		Comment
						Euro	Dollar	
OEmarket	PD-20	2	0.85	1250 - 1600	2	35		
	PD-A-30		0.95	1100 - 1650	3	32		
	Bookham PT10G	10	0.8	1310 - 1575	11.5		590	With transimpedance amplifier
	PD-50	3	0.95	1100 - 1650	5	56		
Go4Fiber	GDCS985	3	0.90	1100 - 1650	3		80	
	Emcore R2860E	2.5	0.8	1280 - 1580	9		99	With transimpedance amplifier
	Agere R2560A	16	0.8	1500 - 1600	13		900	

5.4 Other AOL costs and cost issues

In addition to the component costs also the costs of the fibre-optic cable will play a role in the total AOL costs. Fibre-optic cables have usually a multiple amount of fibres, ranging from 12 to about 200 fibres per cable. The cost level of a fibre-optic cable is also determined by the costs of the mantle. Only at high fibre counts the mantle costs are negligible.

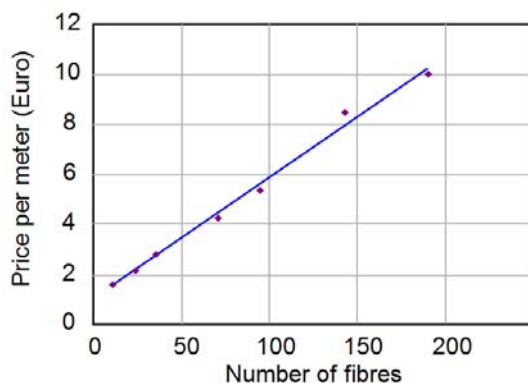


Figure 17 The price per meter of Corning Armored SST Ribbon Cable.

The cost level for the high performance components is still relatively high. This situation can change when a bigger (mass) market for these components arises. An other road towards cost reductions concerns the application of integration techniques. By combining multiple photonic chips in a single package, a reduction of the relative high package costs is obtained. Currently many different integration technology development programs are executed around the globe and slowly integration technologies get introduced in photonic components (e.g. www.luxtera.com).

6 Power consumption of an AOL system

In this chapter the power consumption of the two example AOLs is described. In the calculation of the power consumption of the two AOLs, the power consumption of the driver electronics can be neglected. In all modules, except for the modulator, the monitor diode is not connected.

Table 13 *Power consumption of the external modulation AOL.*

Component	Type	Subsection	Voltage (V)	Current (A)	Power (W)	Comment
CW Laser	EM4, AA1406	Laser Chip	3	0.55	1.65	
		TEC	< 3	< 3	9	
		Thermistor	< 5	< 0.0005	< 0.0025	
Modulator	Photline, MXAN LN10	Modulator Chip	< 20	< 0.0002	< 0.0004	
		Monitor Diode	< 5	< 0.0035	< 0.02	
Detector	Agere, R2560A		15	< 0.013	0	
RF amplifier	MGA-53543		3.3	0.03	0.1	

The maximum power consumption per external modulation AOL will be less than 10.8 W.

Table 14 *Power consumption of an direct modulation AOL.*

Component	Type	Subsection	Voltage (V)	Current (A)	Power (W)	Comment
Laser	LDM1550		1	0.02	0.02	
Detector	PD-50		3	0.001	0	
RF amplifier	MGA-53543		3.3	0.03	0.1	Two amplifiers are needed

The maximum power consumption per direct modulation AOL will be less than 0.22 W.

7 Analog Optical Links: discussion and conclusions

7.1 Design and performance of analog optical links

In the previous chapters both the performance of external modulation and direct modulation links is treated. For an external modulation AOL a link gain of about -15 dB and a dynamic range of ~55 dB can be obtained for a bandwidth of 1 GHz. For a direct modulation AOL a link gain of about -27 dB and a dynamic range of 47 dB can be obtained for a bandwidth of 1 GHz. In case a larger frequency band need to be supported, the amount of noise power in the link will increase, resulting in a smaller dynamic range (see Table 3 for 1 Hz and 1 GHz IMF3s).

For a number of systems this AOL performance is sufficient. In case better AOL performance is needed, a number of solutions are available. The link gain and thus the dynamic range of direct modulation links is increased by applying improved matching circuits. Also more advanced, (coherent) modulation/detection techniques are available with which the NF and dynamic range can be improved (e.g. [8]). Linearization techniques for reducing the modulator and laser distortions will lead to an improvement of the dynamic range as well.

The link gain in an AOL can be increased by applying optical amplification in its optical path. A drawback of this approach is the additional, amplifier related, noise in the AOL which will lead to a higher noise figure.

7.1.1 Analog optical link improvements

Further AOL improvements need to come from further laser and modulator improvements. In case of direct modulation AOLs, lasers with a higher slope efficiency are needed, while for external modulation AOLs this improvement is needed for its modulator. This technology is currently being developed [9], [10]. Another method for improving the slope efficiency of the laser is by cascading multiple single lasers. In this way slope efficiencies >1 can be obtained [11], resulting in positive link gain levels.

Noise figure and dynamic range improvements will be obtained in case the noise level of DFB lasers is further reduced. Since the RIN level is directly related to the optical output power of the laser, higher power lasers are needed. In the past years the DFB output power has slowly increased from ~50 mW about five years ago to ~100 mW today. This development, which is expected to continue, will not only lead to better RIN levels but also provides improved link gains in external modulation AOLs.

Additional link gain and NF improvement are obtained with the use of doped fiber lasers or doped fiber oscillators, which are able to provide optical powers up to 1 W at low RIN levels (~170 dB/Hz).

In case link gain is of great importance while broadband performance is not needed, the bias of the MZI modulator in external modulation AOLs can be adjusted for optimizing the link gain. In this way link gains up to 14 dB can be obtained and a low NF (~ 3 dB) can be realized at the expense of a much smaller operational bandwidth [12].

7.2 Implementation of AOLs in analog electronic systems

For the SKA system, signals in a relative wide frequency band needs to be transferred and processed. For the transfer of these signals in the front-end of the system optical analog link technology is available, which will help to satisfy the SKA needs and requirements.

To make the implementation of analog optical link (AOL) technology in the SKA system as easy as possible, the analog optical link should be considered as a RF component in the design phase of the analog electronic system, with its own insertion loss, NF and distortion levels. In a separate track the AOL design can be performed.

In Chapter 4 the implementation of AOL technology in a RF system is described. It is shown that, in spite of the limited link gain and relatively high NF of the AOL, a good RF system performance is obtained, with a regular noise figure. Moreover, in Figure 14 it is shown that at higher optical power levels in the AOL the RF system noise figure is limited by the antenna / LNA combination.

The dynamic range of ~50 dB, that is obtained with our example systems is already fitting in with the requirements of many systems. Once one or more of the mentioned AOL improvements are applied, a further dynamic range improvement will follow.

In Chapter 5 the cost levels of the various components are described. In case of the direct modulation AOL these levels are acceptable, while for the external modulation AOL the cost level is relatively high. In the latter case the required cost reductions can be obtained using e.g. component integration techniques.

8 Comparison all electronic – photonic signal transfer

For the transfer of analog signals both coaxial cable and analog optical link technologies are available. In determining which technology type is most suitable for a (sub)system, a number of issues play a role. In this chapter the characteristics AOL and coax technology are described and compared.

8.1 Characteristics of coaxial cable links and analog optical links

8.1.1 Characteristics of coaxial cable connections

For the transfer of low frequency (<1 GHz) signals many types of coax are available with good performance an a cost level in the order of 5 Euro per meter. For frequencies beyond 1 GHz coaxial cables with a price level per meter of several 100 Euros

For comparing the coax based high frequency technology with the fiber-optic signal transfer technology that is described in this document, the performance characteristics of a number of coax cable types are given in Table 15.

Table 15 Performance / characteristics of three high frequency coax cable types.

	Unit			
Manufacturer		Radiall	Huber & Suhner	Micro-coax
Type		SHF5OD low loss	S04212_B low loss	UFF092F low loss
Material		Silver, copper, PTFE	Silver, copper, SPE	Silver, copper, PTFE
Insertion loss at 1/5/15 GHz	dB/m	0.26 / 0.61 / 1.1	0.3 / 0.8 / 1.5	0.76 / 1.7 / 3.2
Connection type		connector	connector	connector/soldering
Cable diameter	mm	6.25	5.30	2.34
Static bend radius	mm	25	53	3.18
Dynamic bend radius	mm	-	106	
Weight	g/m	78	41	16.4
Loss vs. temperature	%/°C	0.2		
Phase change vs. bending	°/360°	< 0.4		< 2
Phase stability vs. temperature		< 1 °/m/GHz (0°C - 90°C)		< 1500 PPM (0°C - 70°C)

In the insertion loss levels, the connector losses are not taken into account. In general, these connector losses are in the order of 0.05 dB.

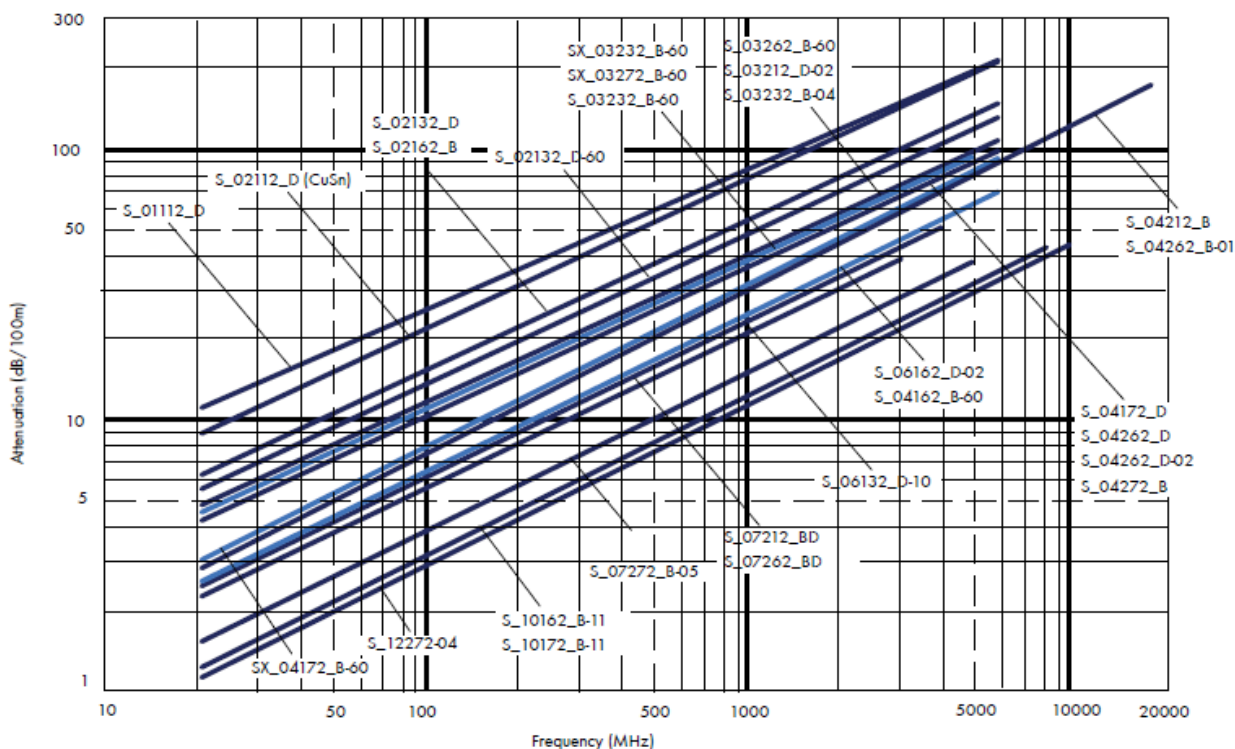


Figure 18 RF cable attenuation of the Huber+Suhner low loss, 50 Ohm, coax cable .

The information in Table 6 shows that at elevated frequencies coaxial cables already introduce a large RF loss (> 10 dB) for relative short transmission distances. Moreover, beyond 50 meter transmission distance, insertion losses are above 35 dB for frequencies beyond 5 GHz. In high performance links, this high level of insertion loss is difficult to compensate with RF amplification, due to intermodulation issues.

Although broadband performance can be obtained in coax based links, the strong frequency dependence of their attenuation will result in different RF levels at different frequencies. For a proper broadband operation this frequency dependence needs to be compensated by equalization, which is usually realized by adding additional RF loss at the lower frequencies. As such, the RF loss in a link is equal to the RF loss at the highest supported frequency.

For links with only a few connections (i.e. cables), the diameter and radius of the combined cable may be acceptable. However, in case large amounts of connections are needed in a link, a bundle of cables needs to be applied, resulting in a large diameter link with a bend radius that is much bigger than the single cable radius. In the latter case the cable weight will also become an issue.

8.1.2 Characteristics of analog fiber-optic connections

For analog optical links mature and space qualified components are available. The RF loss and frequency dependence of an analog optical link (AOL) depends on the configuration of the link and the performance of its components. Short range (100s of meters), high performance AOLs have a RF loss in the order of 15 dB up to 60 GHz, using COTS components.

In contrast to a coaxial cable link, which has a RF loss that depends mostly on the length of the cable, the RF loss of an AOL is introduced at the electrical/optical interfaces. Once in the fibre, the RF signals have an RF loss of ~0.5 dB/km, independent of the employed RF frequency. In the 10 meter range this fiber based RF loss can be neglected. The RF signal loss at the AOL interfaces is described in Section 3.

8.1.2.1 Mechanical and stability characteristics

The diameter of a bare optical fiber is 125 micrometer. For protection of this fiber a tight buffer is applied which has a diameter that ranges from 250 μm to 900 μm . Additional protection is obtained by applying a jacket which has a diameter of ~ 2 mm. Within the jacket multiple (~ 15) tight buffered fibers can be applied. In case large amounts of fibers are needed in a cable, more complex cable structures are employed. In these cables large amounts of fibers can be present while maintaining a small cable diameter (e.g. 144 fibers in a cable with 1.5 cm diameter).

The minimum bend radius of a standard fiber is 25 mm. By applying specialty fiber this radius can be reduced to 10 mm. Since multi-fiber cables do not have a rigidity problem, these minimum bend radii can also be obtained in case a multi-fiber cables are applied.

The weight of a fiber-optic cable is determined by the weight of the buffer, jacket and other protection layers. The bigger multi layer / multi-fiber (~ 100) cables will have a weight of ~ 30 g/m. In the case of multiple fibers in a single jacket, the weight will be in the order of 1 g/m.

An overview of the mechanical and stability characteristics of optical fibers are given in Table 7.

Table 16 Performance and characteristics of optical fiber.

	Unit		Remark
Insertion loss	dB/km	0.25	@ 1550 nm
Connection type		Connector, splice	
Cable diameter	mm	0.125	Without mantle
Bend radius	mm	10	Spec.: ITU-T G.657
Weight	g/m	0.1	$\rho_{\text{glass}} = 2500 \text{ kg/m}^3$
Loss vs. temperature	%/ $^{\circ}\text{C}$	0	
Phase change vs. bending	$^{\circ}/360^{\circ}$		
Phase stability vs. temperature	PPM	< 595	between $0^{\circ}\text{C} - 70^{\circ}\text{C}$, $\alpha_{\text{glass}} = 8.5 \text{ }^{\circ}\text{C}^{-1}$

8.2 Coaxial cable links and analog optical links: a RF performance comparison

In Table 6 and Table 7 the performance and characteristics of optical fibers and their coax counterparts are given. By comparing both, it can be concluded that with respect to space envelope and weight, an optical fiber will provide a strong improvement. Also its thermal and mechanical (bending) properties are equal or better.

When looking into more detail to the RF properties of AOLs in comparison to their co-ax counterparts, it is clear that from a RF loss (link gain) point of view AOLs are to be preferred at higher frequencies and longer transmission distances and in case broadband performance is needed. For every specific case these three items (frequency, transmission distance, bandwidth) need to be addressed in order to make the right choice.

The noise figures of coax cables and AOLs have a different background. In the AOL case the NF is determined by both the RF loss and the AOL noise sources, while for a co-ax only the RF loss is relevant. The AOL NF will be higher than the co-ax NF in a number of cases. However, since the AOL is usually placed after one or more RF amplifiers, the impact of a higher AOL NF is in many cases small, as is shown in Subsection 4.2.3.

The NF situation also holds for the distortion: co-ax does not introduce any additional distortion, while AOLs do. To avoid AOL distortion spurs in the RF output of the optical link, the AOL has a requirement on its RF input power level (see Figure 6). The AOL distortion level in combination with the noise level in the link determine the dynamic range of the AOL. In AOLs the levels of both are such that dynamic ranges of about

50 dB can be obtained for a bandwidth of 1 GHz. In smaller frequency bands a larger dynamic range is available.

In general it can be concluded that currently mature optical analog link technology is available with which AOLs can be constructed that are applicable in many situations and systems. The AOL systems will not just be a replacement of the current co-ax based links; they will also provide a broad(er) band and transmission distance independent performance in combination with big mechanical and RFI advantages.

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