Extinction ratio and dispersion penalty effect on 10 Gb/s single channel links.

Krister Frojdh

Krister.Frojdh@optotronic.com

I. BAKGROUND

In 10 GE, specification up to 40 km single channels links are planned for. For SONET OC192/STM64 separate specifications are used for the transmitted average power (P_{av},), the extinction ratio (ER) and the dispersion penalty (δ_{di}). For the 10GE it is possible to copy this specifications. However this specification seem most appropriate for external modulator and is not well fitted for DFB-EA, and it totally excludes direct modulated lasers. By defining the standard for 10 GE more flexible one can give 10 GE a cost and performance advantage over SONET/SDH standards.

II. EXTINCTION RATIO AND POWER PENALTY

Two parameters are of interest for the transmitter: The extinction ratio of the transmitter and the dispersion penalty at the maximum dispersion. The penalty is defined as the increase in average power needed to obtain the same bit error rate as an ideal pulse with infinite extinction ratio. The extinction ratio (ER) can be transformed into an extinction ratio penalty:

$$\delta_{EX} = 10\log_{10}\left(\frac{ER+1}{ER-1}\right)$$

This expression is shown in Fig 1.

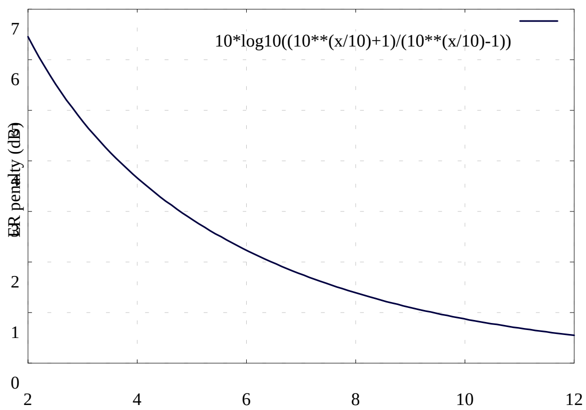

Fig 1 ER penalty as a function of ER

The total power penalty, δ is given by the sum of the extinction penalty, δ_{EX}, and the dispersion penalty δ_{DI}

$$\delta = \delta_{Ex} + \delta_{DI}$$

For the receiver and the system, the power penalty is the relevant parameter. The receiver cannot see any difference between the reduction in eye-opening due to a finite extinction ratio from the transmitter and dispersion induced effects. In SONET/SDH a total power penalty of around 2 dB is accepted. This is however not really an upper limit, systems can be operated at much higher power penalties as long as the transmitter compensates the penalty with a higher output power and as long as no BER floors are generated. This would however make the specification based on transmitter average power difficult to write. A more appropriate choice of specifications, such as OMA, would solve this problem.

III. CALCULATION OF RECEIVER SENSITIVITY

To achieve a BER of 10^{-12}, the received eye must have a quality parameter Q

$$Q > 7$$

corresponding to Q>8.45 dB. For an AC coupled receiver with decision level in the centre, Q is given by

$$Q = \frac{P_{MOD}}{\sigma}$$

where σ is the standard deviation of the noise and P_{MOD} is the modulated power given by

$$P_{\mathrm{mod}}^{dBm} = P_{av}^{dBm} - \delta > 8.45dB + \sigma^{dB}$$

Note that the Optical modulation amplitude OMA is given by

$$OMA = 2P_{\mathrm{mod}}$$

IV. PIN-RECEIVER AND SHOT-NOISE LIMIT

For the 10 GE the intention is to use a PIN diode based receiver. The shot noise limit for a PIN receiver is given by

$$\sigma_s = \sqrt{\frac{2q\Delta f}{R} P_1}$$

where the receiver bandwidth is for a 10 Gb/s receiver and the responsitivity is maximum R=1.25 A/W at 1550 nm. P1 is the power for a received "1"

To move to a dBm scale we must recalculate the power levels as

$$\sigma_s^{dBm} = 10\log_{10}\left(\frac{\sigma}{1mW}\right) = 10\log_{10}(\sigma) + 30$$

$$P_1^{dBm} = 10\log_{10}(P_1) + 30$$

This gives us that the noise level (dBm) is given as

$$\sigma_s^{dBm} = 30 + 5\log_{10}\frac{2q\Delta f}{R} + \frac{P_1^{dBm} - 30}{2} =$$

$$= 15 + 5\log_{10}\frac{2 \cdot 1.6 \cdot 10^{-19} \cdot 7 \cdot 10^{9}}{1.25} + \frac{P_1^{dBm}}{2} =$$

$$= \frac{P_1^{dBm}}{2} - 28.73$$

The power for a received "1" is

$$P_1^{dBm} = P_{av}^{dbM} + 10\log_{10}\left(1 + 10^{-\delta/10}\right)$$

Where ER is the extinction ratio at the receiver, that is, including both ER from transmitter and dispersion penalty.

The minimum receiver average input power to achieve a BER of 10-12 for exceed the shot-noise limit is given by

$$P_{av}^{dBm} - \delta =$$

$$= 8.45 + \frac{P_{av}^{dBm} + 10\log_{10}\left(1 + 10^{-\delta/10}\right)}{2} - 28.73$$

We solve this for the average power

$$P_{av}^{dBm} = 2\delta + 10\log_{10}\left(1 + 10^{-\delta/10}\right) - 40.56$$

This is plotted in Fig 2 together with the sensitivity for a PIN-receiver that is limited to by thermal noise to a sensitivity of -20 dBm. As one can see, the shot noise is not a limitation for a single channel PIN-receiver and a high power penalty can be accepted as long as the transmitter compensates the penalty by a higher output power. For WDM systems with cascaded amplifiers and ad-drop nodes more strict demand must be used for the transmitters, e. g. ITU specifications.

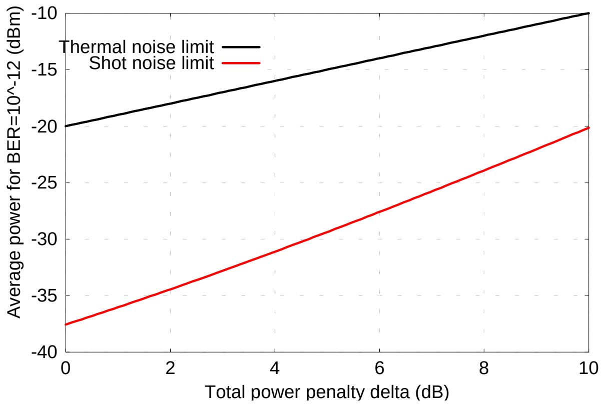

Fig 2 Minimum received average power for BER>10^{-12} for a PIN receiver as a function of the total power penalty δ for thermal noise for a 20 dBm receiver (black line) and shot-nose (red line)

V. Effect of RIN

Another limitation that can set a limit for the maximum acceptable power penalty is the RIN noise of the laser. For a direct modulated laser, the RIN noise decreases with increasing power resulting in a constant absolute level of noise. However as RIN is a relative parameter, the minimum acceptable RIN limit will be dependent of the power penalty.

VI. Effects of multiple reflections

Multiple reflections could be present on the link. If the distance between the reflections is below the coherence length of the source a power variation dependent of the chirp of the source can be generated. The power variation can be expressed as

$$\Delta P = P_1 2\sqrt{R_1 R_2}\cos(\gamma)$$

where γ is the phase between the reflections. The interference could give a reduction in the eye-opening at the receiver.

The effective modulated power at the receiver could in the worst case be reduced to

$$P_{\mathrm{mod},1} = P_{av}10^{-\delta/10} - 2P_1\sqrt{R_1 R_2}$$

This can be expressed as an interference induced penalty contribution δ_{IN}.

$$\delta_{in} = -10\log_{10}\left(10^{-\delta/10} - 10^{\frac{R_1+R_2+6}{20}}\right) - \delta$$

This equation is plotted Fig 3 for R_1=R_2=-20 dB As can be seen, this represents a minor problem for δ<6 dB. In 10GE the worst-case reflection is dependent of the maximum acceptable connector reflection and the maximum reflection for the transmitter and the receiver.

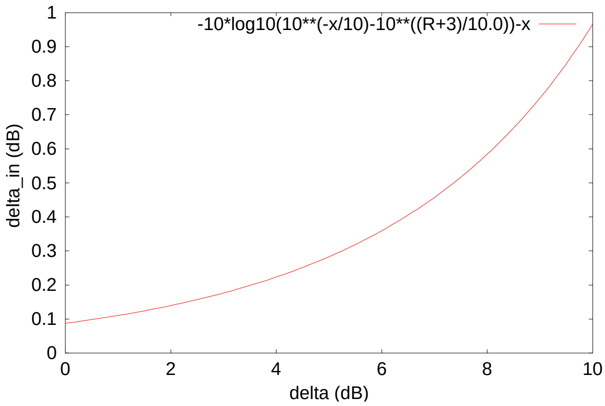

Fig 3 Maximum possible interference induced penalty as a function of total power penalty.

VII. Trade of between ER and dispersion penalty

For all transmitters there is a trade off between achieving a high ER and a good handling of dispersion. This is even true for $LiNbO_3$ modulators. In [1] a ER of 7 dB mimimized the total power penalty for long distances. For 10 GB/s, DFB-EA and direct modulated lasers will be more cost-effective sources and for these an even lower ER should give the optimum value for the total power penalty. As shown in the discussion above one must set a maximum value for the **total** power penalty that is the sum of extinction ratio penalty and dispersion penalty. The transmitter must compensate this total penalty with a higher average power but this is general not a problem for DFB-EA and direct modulated lasers. A higher degree of freedom in balance between power penalty and output power will result in lower price and better distance performance. At 1550 nm, eye-safety is not an issue.

VIII. Optimization of ER and penalty for direct modulated lasers.

A direct modulated laser is a promising component for 10 Gb/s with low cost, high output power and potentially good dispersion handling. For handling the dispersion of 40 km of standard single mode fiber it is necessary to operate a laser at a rather low extinction ratio [2]. A direct modulated laser operated at low ER can actually be capable of handling more dispersion than a modulator. Using a direct modulated DBR laser, transmission over 125 km standard fiber has been obtained [4]. To allow use of direct modulated lasers at 10 GB/s, a total penalty of 5 dB must be accepted, however.

IX. Optimization of ER and penalty for DFB-EA

A DFB-EA is an integrated DFB-laser and electroabsorption modulator. The DFB-laser is operated CW and an electrical high-speed modulation is applied to the modulator. The emitted power is

$$P = P_0 \exp(-L\alpha(V))$$

where P_0 is the output power of the DFB-laser, L is the length of the modulator and α is the modal absorption that is dependent of the voltage V over the modulator. The modal absorption has a approximately linear dependence of the applied voltage. For the rest of the discussion we assume a typical dependence of

$$\alpha(V) = 50 - 50V \ cm^{-1}$$

where V<0 and that the modulation voltage is V_{mark}=0 and V_{space}=-2 V. By using a long modulator, L=200 μm, a high extinction ratio can be obtained. This is however at the expense of a high insertion loss resulting in a low output power. To maximize the handling of losses in the link, we want instead to maximize the modulated power.

$$P_{mod} = P_0 \left[\exp(L\alpha(V_{mark}) - \exp(L\alpha(V_{space})\right]$$

For the example characteristic above, the maximum modulated power is obtained for L=110 μm at an extinction ratio of 4.8 dB. Another problem with using a DFB-EA with ER is the sensitivity for imperfect electrical driving. The relative amplification of an electrical overshoot can be expressed as

$$\eta = V_{mark}' - V_{space} \frac{L\dfrac{d\alpha}{dV}\exp(-L\alpha(V_{mark}))}{\exp(-L\alpha(V_{mark})) - \exp(-L\alpha(V_{space}))}$$

For the linear model above, this amplification factor increases from 1.65 for a 110 μm long modulator to 2.3 for a 200 μm modulator, hence a short modulator with lower extinction ratio is preferable also from this point of view.
A third reason for not operating a DFB-EA at a high ER is the fact that the chirp gets more favorable for long distance transmission with increased absorption. A long modulator must be operated at a lower absorption.

X. SPECIFICATIONS

The standard should be expressed in a way that the variation in power penalty results in different minimum output power. One way to do this is to specify the OMA of the source and allow a maximum dispersion penalty. The most flexible way is however so say that the output power of the laser must compensate its total power penalty for a given dispersion. An example of this is shown in Table 1.

Table 1 Example of a flexible specification. Notice that the numbers should only be considered as examples, not as standard proposal.

Description	**symbol**	**max**	**min**
Extinction ratio penalty	δ_{ER}	4 dB	
Dispersion penalty at 800 ps/nm	δ_{DI}	3 dB	
Total power penalty	$\delta_{ER}+\delta_{DI}$	6 dB	
Average launch power	P_{av}	$0+\delta_{ER}$	$-4+\delta_{ER}+\delta_{DI}$ (dBm)
Relative Intensity noise	RIN	$-140-\delta_{ER}-\delta_{DI}$ (dB/Hz)	

XI. CONCLUSIONS

A more flexible specification will reduce transmitter cost and also allow transmission over long distances. The most difficult problem if one wants to extend the reach is to handle the larger dispersion, not to compensate the increased attenuation. Direct modulated lasers operated at low ER can handle very large distances but do not fit into the standard ITU specification regarding i.e. extinction ratio.10GE has a unique chance to get a distinct advantage over ITU system by a better choice of specifications. This specification will allow optimal use of ITU compatible transmitters but will also allow future more cost effective solutions that can handle long distances.

XII. REFERENCES

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