Optically preamplified receiver with low quantum limit

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Published in:
Electronics Letters

DOI:
10.1049/el:19990828
10.1049/el;19990828

Published: 01/01/1999

Citation for published version (APA):

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Download date: 17. Dec. 2018
Optically preamplified receiver with low quantum limit

1. Tafur Monroy

An optically preamplified receiver configuration results in a very low quantum limit is presented.

Introduction: Optical amplifiers are proven to efficiently enhance the receiver sensitivity of optical communication systems. In optical communications it is common practice to compare the system's ultimate sensitivity in terms of the quantum limit. The (standard) quantum limit is defined as the average number of photons per bit in the optical signal needed to achieve a bit error probability of 10^-9 assuming ideal detection conditions, which for a preamplified receiver means that a large amplifier gain is assumed. In this Letter we present an optically preamplified OOK/DD receiver scheme with a very low quantum limit, which is predicted to outperform previously studied configurations.

System model: The schematic diagram of the studied receiver is illustrated in Fig. 1. The preamplifier is an EDFA (erbium-doped fibre amplifier) which is modelled as a linear optical field amplifier with gain G and AWG (additive white Gaussian) noise n(t) representing the ASE (amplified spontaneous emission) noise. The spectral parameter of n(t) is given by N_s = n_u (G - 1)h, where n_u is the amplifier spontaneous emission factor, h is Planck's constant, and v the frequency. An optical filter f(t) is used to limit the effect of ASE on the system performance, and in the case of WDM (wavelength division multiplexing) systems, to select the desired channel. The incoming signal is a binary sequence of rectangular pulses S(t). At the output of the filter f(t) the signal is denoted by Y(t) and the resultant coloured Gaussian noise by X(t). With the above notation the incident optical field on the photodetector becomes: B(t) = Y(t) + X(t). The optical filter is a finite-time integrator over the bit duration time [0, T], the impulse response r(t) of which is given by

\[ r(t) = \begin{cases} \frac{h}{v} & 0 \leq t \leq T \\ 0 & \text{otherwise} \end{cases} \]  

(1)

The postdetection filter is assumed to be an integrate-and-dump filter. The integration interval T is chosen to be \( T = \Delta T/2 \). The parameter \( d \) is selected so as to yield the lowest bit-error probability.

Performance analysis: For the performance analysis we need a complete statistical description of the receiver decision variable. The moment generating function (MGF) provides us with such statistical information. The MGF for the decision variable Z is given by \( M_Z(s) = M_s(e^{-s}) \), where \( M_s \) is the so-called Poisson parameter \( \Lambda \). Based on the MGF for the decision variable \( Z \), error probabilities are expediently computed by the so-called saddlepoint approximation [2, 3].

The general mathematical form for the MGF of \( Z = S(t) + D(t) \) is given as

\[ M_Z(s) = \exp \left[ -s \int_0^\infty \frac{d^2}{d^2y}(Y(y))\right] \]

(2)

where \( F(s) \) and \( D(s) \) are found by solving the so-called Fredholm integral equations, e.g. [2, 4]. For the present case we have

\[ F(s) = mG^2[H_1(s) + H_2(s)] + \exp \left[ -s \int_0^\infty \frac{d^2}{d^2y}(Y(y))\right] \]

(3)

with

\[ H_1(s) = \frac{8}{\beta \cos \beta} \sin \left[ (2d - 4) \sin \beta \left( 4d - 2 \right) - 2(2d - 4) \right] \]

References

3. HENRY, C.H., O'SULLAGH, N.A., and DUTTA, N.K.: "Optical injection locking of 1.55-µm FP-LDs using FWM to realise the spare sources for WDM systems. The principle was confirmed by an experiment in which the injection locking of the 1.55-µm FP-LD was achieved by injecting the FWM component generated in a U4-shifted DFB-LD. The injection locking occurred up to seven modes away from the central mode of the FP-LD, which corresponded to a wavelength difference of 7.91 nm.

Wavelength range can be realised.

Under those conditions, the locking half bandwidth \( \Delta f \) was calculated as 2.45 GHz. This value agrees well with measurements.

In conclusion, we have proposed a novel intermodulation injection locking for FP-LDs using FWM to realise the spare sources for WDM systems. The principle was confirmed by an experiment in which the injection locking of the 1.55-µm FP-LD was achieved by injecting the FWM component generated in a U4-shifted DFB-LD. The injection locking occurred up to seven modes away from the central mode of the FP-LD, which corresponded to a wavelength difference of 7.91 nm. The locking half bandwidth was 2.42 GHz, and the SMSR was 14.3 dB.

By using this technique, stable spare sources with wide tunable wavelength range can be realised.

© IEE 1999 10 May 1999
Electronics Letters Online No: 19990790
DOI: 10.1049/el:19990790

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...d(202s), and present observed bit D(s) where a transmitted symbol 'one'. The parameter o2 present transmitted bit. Hence the bit sequence of interest is is presented in Fig. 2. We observe that the lowest quantum limit is bo, knowledge, the lowest reported theoretical quantum limit is presented receiver configuration outperforms previously studied schemes. An interesting question, open for study, is which value constitutes the ultimate theoretical lowest quantum limit for optically preamplified OOK/DD receivers.

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**Fig. 2** Quantum limit against integration interval dT

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**Gaussian approximation:** The error probabilities may also be computed by using the common Gaussian approximation for the statistics for the receiver decision variable. This approximation requires that the mean E, and variance Var, of the parameter λ to be known. These magnitudes can be determined either by using the properties of the MGF or by solving a set of integrals involving X(t) and the autocorrelation of X(t) [4]. The resultant expressions are

\[
E_\lambda = mG[2(2d - d^2 + d^3)/6] + (b_1 + b_2)d^2/12 + (b_1 - b_2) + b_2b_0](d^2/2 - d^3/6)
\]

\[
Var_\lambda = mG[2(2400d - 160d^3 - 2d^4 + 35d^5)]
\]

\[
(b_1 - b_2b_0)(60d^2 + 2d^3 - 25d^4)
\]

\[
+ (b_1^2 + b_2^2/120)](15d^4 - 2d^5)
\]

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**Summary:** We have shown that if the optical filter is a finite-time integrator and the postdetection filter an integrator over a small interval centred around the end of each bit interval then a quantum limit of 16.2 photon/bit can be achieved. Although a finite-time integrator optical filter (corresponding to a filter with a sinc shaped transfer function) is probably difficult to realise, the presented receiver configuration outperforms previously studied schemes. An interesting question, open for study, is which value constitutes the ultimate theoretical lowest quantum limit for optically preamplified OOK/DD receivers.

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**References**


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**OTDM applications of dispersion-imbalanced fibre loop mirror**


Improvement of the signal quality from 10GHz directly-modulated sources and crosstalk suppression in an 80Gb/s OTDM system are demonstrated for the first time by means of nonlinear switching in a dispersion-imbalanced fibre loop mirror (DILM).

The nonlinear transformation of optical pulses in fibre interferometers has long been of interest for the purposes of high-capacity data transmission. Recently, a novel approach has been applied to the generation of high-quality optical pulses from simple, directly-modulated sources in a compact fibre device based on self-switching in a dispersion-imbalanced fibre loop mirror (DILM) [1, 2]. High quality femtosecond and picosecond pulse generation have been demonstrated from an ordinary gain-switched laser diode, with pedestal extinction ratio > 20dB in the output signal, this figure being limited by the resolution of the apparatus used at the time.

In this Letter, we describe an application of the above method for pulse quality improvement in conjunction with an electroabsorption modulator (EAM). Furthermore, the same method is implemented for interchannel crosstalk reduction after demultiplexing. Pulse characterisation is achieved using a novel correlation technique (coherence time analysis) which provides a dynamic range of 70dB [3].

The unique switching properties of the DILM allow considerable improvements in the BER performance of the demultiplexer, making it possible to faithfully retrieve the data even from an inadequately demultiplexed data stream. We demonstrate that while high capacity systems may be implemented using multiple high specification components [4-6], the DILM allows either a significant relaxation of the component specification, or alternatively, offers the potential for greatly increased capacity.