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mode (denoted by the arrow in Fig. 3a) was seven modes away from the centre mode of LD_3 , which corresponded to a wavelength difference of 7.91 nm. When the injection locking took place, the centre mode jumped to the injected mode, and other modes were clearly suppressed as shown in Fig. 3b. The peak power ratio of the locked mode to the injected FWM component was 24.2 dB, and the sidemode suppression ratio (SMSR) was 14.3 dB. Note that the SMSR was somewhat degraded because the amplified spontaneous emission noise of the EDFA as well as FWM component was injected into LD_3 .

Under those conditions, the locking half bandwidth Δf was 2.42 GHz. The theoretical value of the locking half bandwidth is given by [6]

$$\Delta f = \frac{1}{4\pi\tau_{ph}} \sqrt{\frac{P_{FWM}}{P_{LD3}}} \quad (1)$$

where τ_{ph} is the photon lifetime, and P_{FWM} and P_{LD3} are the FWM power and the LD_3 power inside the cavity of LD_3 , respectively. By substituting the typical value of $\tau_{ph} = 2.0 \times 10^{-12}$ [s] into eqn. 1 and using the measured value of $P_{FWM}/P_{LD3} = -24.2$ dB, the locking half bandwidth Δf is calculated as 2.45 GHz. This value agrees well with measurements.

In conclusion, we have proposed a novel intermodal 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 μ m FP-LD was achieved by injecting the FWM component generated in a $\lambda/4$ -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.

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Optically preamplified receiver with low quantum limit

I. Tafur Monroy

An optically preamplified receiver configuration resulting 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.

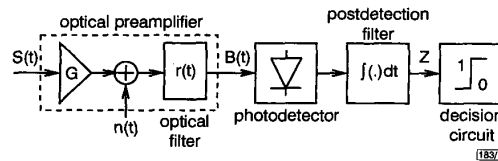


Fig. 1 Optically preamplified OOK receiver

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 $N_s = n_{sp}(G-1)h\nu$, where n_{sp} is the amplifier spontaneous emission factor, h is Planck's constant, and ν the optical frequency. An optical filter $r(t)$ 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 $r(t)$ 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

$$r(t) = \begin{cases} \frac{1}{T} & 0 \leq t \leq T \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

The postdetection filter is assumed to be an integrate-and-dump filter. The integration interval I is chosen to be $[T - dT/2, T + dT/2]$. 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 receiver decision variable Z is given by $M_Z(s) = M_\Lambda(e^s - 1)$, where Λ is the so-called Poisson parameter [1]. For an integrate-and-dump postdetection filter $\Lambda = \frac{1}{2} \int_I |Y(t) + X(t)|^2 dt$. Based on the MGF for the decision variable Z , error probabilities are expeditiously computed by the so-called saddlepoint approximation [2, 3].

The general mathematical form for the MGF of Λ , $M_\Lambda(s) = E\{e^{s\Lambda}\}$, is well known, e.g. [2], and can be represented as

$$M_\Lambda(s) = [D(s)]^{-1} \exp[F(s)] \quad (2)$$

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

$$F(s) = mG[b_0^2 H_1(s) + (b_{-1}b_0 + b_0b_1)H_2(s) + (b_{-1}^2 + b_1^2)H_3(s)] \quad (3)$$

with

$$H_1(s) = \frac{s}{\beta \cos \beta} [\sin x(2d-4) + \sin \beta(4-d^2/2-2d)]$$

$$H_2(s) = \frac{2}{\sigma^2 \beta \cos \beta} [\sin \beta - \sin(x)] - d \frac{\cos x}{\sigma^2 \cos \beta}$$

$$H_2(s) = \frac{s}{\beta \cos \beta} [d \sin \beta - d \sin x - d^2 \sin \beta / 2]$$

$$+ d \frac{\cos x}{\sigma^2 \cos \beta} + \frac{2}{\sigma^2 \beta \cos \beta} [\sin x - \sin \beta]$$

$$H_3(s) = \frac{1}{\beta \cos \beta} \left[s d^2 \sin \beta / 4 \right.$$

$$\left. - \frac{1}{\sigma^2} (d \beta \cos x / 2 + \sin \beta - \sin x) \right]$$

where m is the number of received photons in an optical pulse for a transmitted symbol 'one'. The parameter $\sigma^2 = n_p(G - 1)$, $\beta = \sqrt{2\sigma^2 s}$, and $x = \beta(1 - d/2)$. The Fredholm determinant is given by $D(s) = \cos(\sqrt{2\sigma^2 s d})$. We observe that for this receiver configuration only a single past and one succeeding bit (with respect to the present observed bit b_0) produce intersymbol interference on the present transmitted bit. Hence the bit sequence of interest is (b_{-1}, b_0, b_1) .

A plot of the quantum limit against the integration interval dT is presented in Fig. 2. We observe that the lowest quantum limit is 16.2 photon/bit for a factor $d = 0.12$ and a value of $G = 20$ dB. If the value of G is large and the integration interval dT is made small and optimised (yielding the lowest error probability), the proposed receiver scheme has a lower quantum limit compared to the previously studied configurations; for instance, to the author's knowledge, the lowest reported theoretical quantum limit is 38.4 for a receiver with an optical matched filter [3, 5]. The matched filter situation is the case when the optical signal is assumed to pass the optical filter undistorted and that $X(t)$ is Gaussian band-limited (ideal bandpass filter assumed).

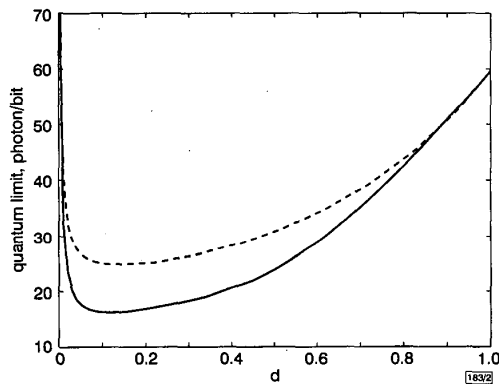


Fig. 2 Quantum limit against integration interval d

— saddlepoint
 ---- Gaussian approximation

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_Λ and variance Var_Λ 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 $Y(t)$ and the autocorrelation function of $X(\tau)$ [4]. The resultant expressions are

$$E_\Lambda = mG \left[b_0^2 (2d - d^2 + d^3/6) + (b_{-1} + b_1) d^3 / 12 \right. \\ \left. + (b_{-1} b_0 + b_1 b_0) (d^2 / 2 - d^3 / 6) \right] \quad (4)$$

$$\text{Var}_\Lambda = mG \sigma^2 \left[\frac{b_0^2}{120} (240d^2 - 160d^3 - 2d^5 + 35d^4) \right. \\ \left. + \frac{(b_{-1} b_0 + b_1 b_0)}{120} (60d^3 + 2d^5 - 25d^4) \right. \\ \left. + \frac{(b_{-1}^2 + b_1^2)}{240} (15d^4 - 2d^5) \right] \quad (5)$$

Fig. 2 shows the result of the Gaussian approximation for the quantum limit (dotted line). The minimum value is 24.8 photon/bit for an integration interval $d = 0.12$.

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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OTDM applications of dispersion-imbalanced fibre loop mirror

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Improvement of the signal quality from 10GHz directly-modulated sources and crosstalk suppression in an 80Gbit/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.