Direct modulation 565 Mb/s PSK heterodyne system with solitary SL-QW-DFB lasers and novel suppression of the phase transition periods in the carrier recovery

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Summary:

Performance of a synchronous PSK heterodyne receiver is improved if the squared IF signal in the carrier recovery branch is switched off periodically by the recovered clock. Using this technique we demonstrate a 61.4 dB power budget in a PSK heterodyne system based on solitary DFB lasers and direct laser modulation.

Introduction:

In spite of their high bandwidth efficiency and receiver sensitivity not many PSK heterodyne systems have been reported. Common to all previous experiments is that (i) external-cavity-, gas-, or Nd:YAG-lasers were employed, and (ii) external phase modulators impaired the power budget; see, e.g., [1-6]. We show here why carrier recovery is difficult to implement for high laser linewidths, long transition times between phase states, and pattern sequences with non-zero energy at low frequencies. This problem is overcome by a novel suppression of the phase transition periods in the carrier recovery branch of the heterodyne receiver [7]. Using this technique, we then present, to our knowledge, the first synchronous PSK experiment that does not suffer from the mentioned drawbacks. Solitary DFB lasers, without external linewidth narrowing, are employed. The transmitter laser is directly modulated by a bipolar [8, 4] pulse pattern.

Problem statement and solution:

Carrier recovery by a PLL (or bandpass filter) at the center IF is straightforward if a residual carrier is transmitted. Unfortunately, this requires a compromise to be adopted between achievable receiver sensitivity and allowable PLL bandwidth which in turn severely limits the tolerable laser linewidth. In an alternative implementation [1, 3-5] a squarer, bandpass filter (or PLL) and subsequent frequency divider by two recover the carrier.

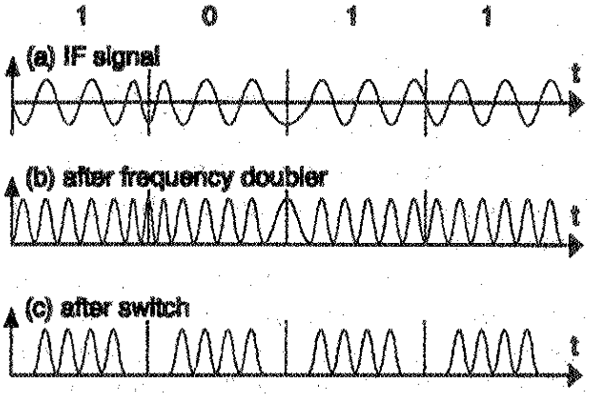

Fig. 1: Signals in PSK heterodyne receiver

Fig. 1a shows the IF signal in a PSK heterodyne receiver (Fig. 2) if a bit sequence 1011 is transmitted. In the phase transition periods 1 -> 0 and 0 -> 1 the instantaneous frequency is changed due to either an optical phase modulator or direct modulation of a semiconductor transmitter laser by short current pulses. These frequency changes are also present in the signal (Fig. 1b) after the squarer which is used for frequency doubling in the carrier recovery branch of the receiver. The subsequent bandpass filter BPF passes sidebands near the frequency-doubled carrier, which results in phase jitter also of the recovered carrier. The effect is aggravated if the BPF width is chosen high (to accomodate large laser linewidths), if the phase transition periods are long (for direct modulation of the TX laser rather than external phase modulation, and at high data rates), and if the data pattern has substantial energy in the low-frequency region. The problem is non-

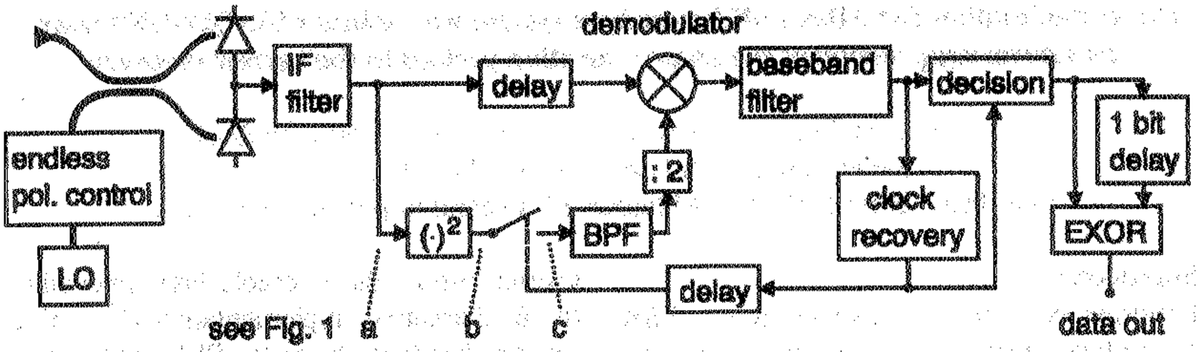

Fig. 2: PSK heterodyne receiver with suppression of the phase transition periods in the carrier recovery branch by a switch

existent if phase modulation is achieved by pure amplitude modulation with zero quadrature component. This is the case for certain optical Mach-Zehnder modulators biased at the quadrature point [4] and for radio-frequency modulation based on multipliers.

A solution to the problem is to cut out all phase transition periods anywhere in the carrier recovery branch of the receiver but before the BPF [7]. In Fig. 2 a switch, driven by the appropriately delayed recovered clock signal, is used for this purpose. The detrimental effect of energy loss in the off-periods is more than compensated by the removal of phase jitter in the signal of Fig. 1c. The beneficial action of the switch on carrier recovery was previously confirmed in numerical calculations. The scheme can also be used for m-ary PSK.

The intrinsic phase ambiguity of the recovered carrier, present in all m-ary PSK carrier recovery schemes based on frequency multiplication and division, is removed by differentially encoded data at the transmitter and differential decoding at the receiver output in an EXOR gate after the decision circuit.

Experiment:

A 565 Mb/s direct modulation bipolar DPSK system [9] with endless polarization control was adapted to accomodate synchronous PSK. Strained layer quantum-well (SL-QW) DFB lasers similar to [10] with up to 38 mW output power are used as transmitter and local oscillator lasers in the 1.5 µm wavelength region. The transmitter phase is directly modulated by applying short current pulses to the laser. Bipolar pulses are chosen to eliminate the influence of non-uniform FM response of the transmitter laser [8, 4].

Center IF and unmodulated IF linewidth are 1085 and 1 MHz, respectively. The BPF has a width of 80 MHz, centered around twice the IF. Fig. 3 (top) shows the measured spectrum of the squared IF signal before the switch, corresponding to the waveform of Fig. 1b. After the switch (Fig. 3, bottom, corresponding to the waveform of Fig. 1c), the signal-to-noise ratio of the frequency-doubled carrier at 2170 MHz to the directly surrounding noise is improved by 1 .. 4 dB. It is believed that pattern-dependent phase

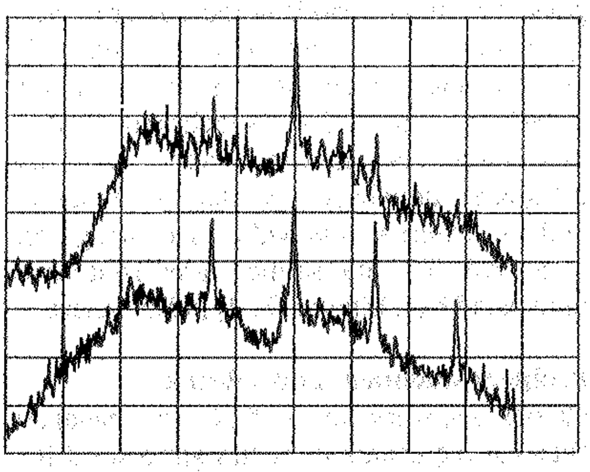

Fig. 3: Spectrum of squared IF signal before the switch (top trace), and after the switch (bottom trace, displaced by 3 div.). Center 2170 MHz, span 4 GHz, 10 dB/div.

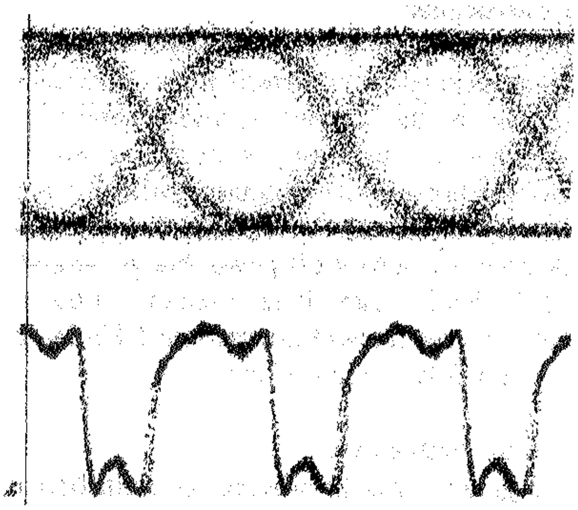

Fig. 4: 565 Mb/s eye pattern (top) and recovered clock signal used for switching (bottom; LOW = off, HIGH = on)

modulation is reduced by the switch. The induced amplitude modulation at 565 MHz, and amplitude noise, are removed by the combined action of BPF and a following limiting amplifier (not shown in Fig. 2).

Fig. 4, bottom trace shows the recovered clock signal which drives the switch. A clear eye pattern is seen in Fig. 4, top trace. Fig. 5 shows measured bit error ratios in the receiver for 2^7-1 and 2^{15}-1 PRBS. In the conventional scheme, without switch, the phase jitter of the recovered carrier causes severe sensitivity degradation in form of BER curve bending. With the switch in operation, this effect is removed substantially because the phase transition periods are suppressed. Receiver sensitivities of -56.4 dBm (ηP; 33 photoelectrons/bit) and -56.0 dBm are realized for 2^7-1 and 2^{15}-1 PRBS, respectively. With η = -1.8 dB and a launched transmitter power of +7.2 dBm a loss span of 61.4 dB is obtained for the 2^{15}-1 PRBS. A 94 km long single-mode fiber and subsequent attenuators are employed for transmission. The polarization controller has a cycle time of 2.8 ms and can track endless polarization fluctuations as fast as 12 .. 18 rad/s with a receiver sensitivity loss of less than 0.22 dB.

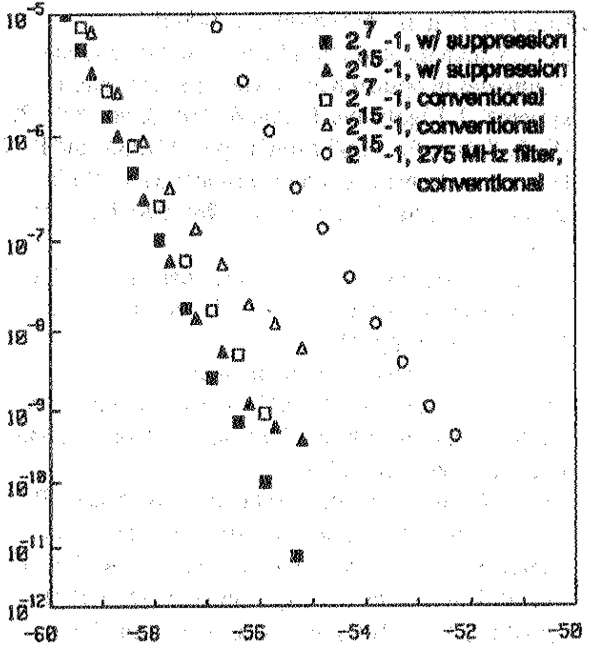

Fig. 5: Measured BER vs. power ηP [dBm]

Discussion:

At low bit error incidence the following two kinds of bit errors can easily be discerned: Conventional single bit errors in the decision circuit manifest themselves as double errors after the differential decoder. Cycle slip errors of the frequency divider cause polarity changes of the demodulated signal, but only single errors after the differential decoder. With a 275 MHz wide BPF the SNR at the divider was insufficient. Single bit errors were observed and a sensitivity of about -52.8 dBm (ηP; 2^{15}-1; see Fig. 5) was measured for this case (without phase transition period suppression). With the improved, 80 MHz wide BPF double errors dominate at medium BER and probably also at high BER (where this is not discernible). But the pattern-length-dependent bending of the curves in Fig. 5 at low BER is due to increasingly frequent single errors. One suspected reason for this is that the finite impulse response of the 700 MHz wide IF filter broadens the phase transition periods, other than depicted in Fig. 1, and makes it impossible to cut them out completely. As a solution one could tap the signal for carrier recovery before the IF filter (or else remove the IF filter) and place the switch, followed by an IF filter, before the squarer. According to our experience, some kind of IF filtering is needed before the squarer in order to prevent SNR degradation of the frequency-doubled signal due to squared noise.

Transmission at +9.7 dBm launch power results in a rebroadened unmodulated IF linewidth of 1.6 MHz. In this case a BER floor of about $2*10^{-9}$ is observed even for the 2^7-1 pattern, and a higher floor for the 2^{15}-1 pattern. It is therefore strongly believed that the observed BER curve bending will also decrease for IF linewidths below 1 MHz. Optimization of BPF width and, most importantly, further minimization of BPF group delay distortion should work in the same direction. We think our recommendation of further linewidth reduction in the present experiment is not inconsistent with the pioneering experiment [3] where a 2 MHz IF linewidth was tolerated, because (i) the externally narrowed IF line in Fig. 2 of [3] falls off more rapidly than a Lorentzian line, and (ii) an external phase modulator was used in [3], rise-times of phase modulators being usually much faster than our 0.6 ns laser drive pulse width.

The off-ratio of the recovered clock at the switch, estimated as 36% from Fig. 4, bottom, is about equal to the duty cycle of the laser drive pulses. Choice of the optimum switching ratio is found to be uncritical. Almost equal benefit is obtained for off-ratios ranging from 25% to 60%.

The 2.5 dB difference between the measured sensitivity $\eta P = -56.4$ dBm for a 2^7-1 pattern and the shot noise limit are attributed as follows: Thermal noise (0.12 dB), polarization control (<0.1 dB), and error ratio doubling caused by differential decoding (0.15 dB). The phase transitions, estimated from the duty cycle of the laser drive pulses, cause a 0.8 dB penalty, assuming an ideal laser and matched filter detection. Most of the remaining 1.4 dB are attributed to intersymbol interference and pulse distortion in the IF and baseband circuits of the receiver, and in the transmitter.

Conclusions:

Performance of a synchronous PSK heterodyne receiver is improved if the squared IF signal in the carrier recovery branch is switched off periodically by the recovered clock. Choice of the optimum switching ratio is very uncritical. Using this technique we demonstrate a 61.4 dB power budget in a 565 Mb/s PSK heterodyne system based on solitary, not linewidth-narrowed DFB lasers, and direct laser modulation.

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