23cm PSK packet-radio RTX for 1.2Mbit/s user access

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1. Why biphase PSK modulation?

Upgrading the packet-radio network to higher data-rates also requires using more efficient modulation and demodulation techniques both to reduce the signal bandwidth and to increase the radio range of the system. In particular, inefficient modems coupled to standard FM transceivers have to be replaced with custom-designed radios for data transmission. Considering the bandwidth and TX power available to radio-amateurs, it is necessary to switch to coherent demodulation techniques at data-rates around 100kbit/s in terrestrial packet-radio and at even lower data-rates in satellite communications.

One of the simplest forms of digital modulation, that can be demodulated in a coherent way, is bi-phase PSK. The usual amateur approach to implement biphase PSK is to use already existing equipment like linear transverters or SSB transceivers coupled to custom-designed modems operating at an intermediate frequency. While this approach may be acceptable for satellite work, it is rather complex and inconvenient for conventional terrestrial packet-radio.

On the other hand, professionals developed very simple and efficient digital radios like GSM cellular telephones. Professionals also found out that they can not use the frequency spectrum efficiently with narrow-band FM radios: all new cellular-phone systems use high-speed TDMA techniques or even spread-spectrum modulation. If we radio-amateurs want to improve our digital communication, it is therefore necessary to develop and build new equipment. The only place for obsolete narrow-band FM equipment is a museum!

Maybe PSK modulation is not considered very efficient by many amateurs, since it is used on satellites at data rates of only 400bit/s or 1200bit/s. On the other hand, in Slovenia (S5) we installed our first 1.2Mbit/s PSK links in 1995, operating in the 13cm amateur band at 2360MHz. This equipment resulted very reliable and the PSK links never failed, even when the 70cm and 23cm 38.4kbit/s links were out due to heavy snowfall in the 1995/96 winter.

The 13cm PSK 1.2Mbit/s link transceiver used in these links (shown in Weinheim in September 1995) was only the first attempt towards a dedicated PSK radio. The 13cm transmitter was simplified by using direct PSK modulation on the output frequency, but the 13cm receiver is still using a double down-conversion followed by a conventional IF squaring-loop PSK demodulator. The construction of this transceiver is not simple: there are several shielded modules and especially the double-conversion receiver requires lots of tuning.

2. Direct-conversion PSK data transceiver

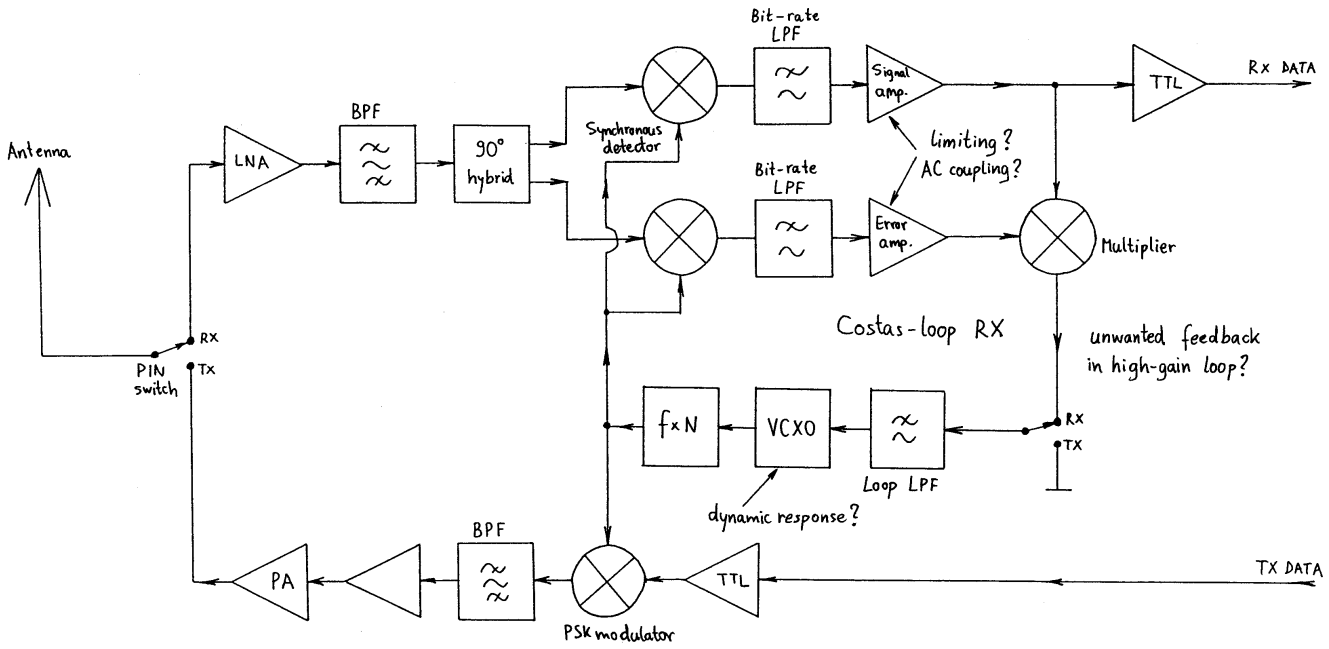


Fig. 1 - Direct-conversion PSK data transceiver.

Similarly to a SSB transceiver, a PSK transceiver can also be built as a direct-conversion radio as shown on fig.1. The Costas-loop demodulator can be extended to include most of the amplification in the receiving chain. Since such a receiver does not require narrow bandpass filters, the construction and alignment can be much simplified. In addition, some receiver stages can also be used in the transmitter (like the local oscillator chain) to further simplify the overall transceiver.

A direct-conversion PSK receiver also has some problems. Limiting is generally not harmful in the signal amplifier, however it increases the noise in the error amplifier chain. In practice the loop bandwidth has to be decreased, if no AGC is used and both amplifiers operate in the limiting regime. It is also very difficult to have both amplifiers DC coupled as required by the theory. If AC coupled amplifiers are used, randomization (scrambling) has to be applied to the data stream and some additional noise is generated. However, in a well-designed, direct-conversion PSK receiver the signal-to-noise ratio degradation due to AC coupling can be kept sufficiently small.

Building a real-world, direct-conversion PSK receiver one should also consider other unwanted effects. For example, the Costas-loop demodulator includes very high-gain stages. Unwanted effects like AM modulation on the VCO or FM-to-AM conversion in the multiplier stages can lead to unwanted feedback loops. However, the most critical component seems to be the VCO.

In a practical microwave PSK transceiver the VCO is built as a VCXO followed by a multiplier chain. Although the static frequency-pulling range of fundamental-resonance and third-overtone crystals is sufficient for this application, their dynamic response is totally unpredictable above 1kHz. The latter may be enough for full-duplex, continuous-carrier microwave links, but it is insufficient for CSMA

packet-radio, where a very fast signal acquisition is required.

3. Zero-IF PSK data transceiver

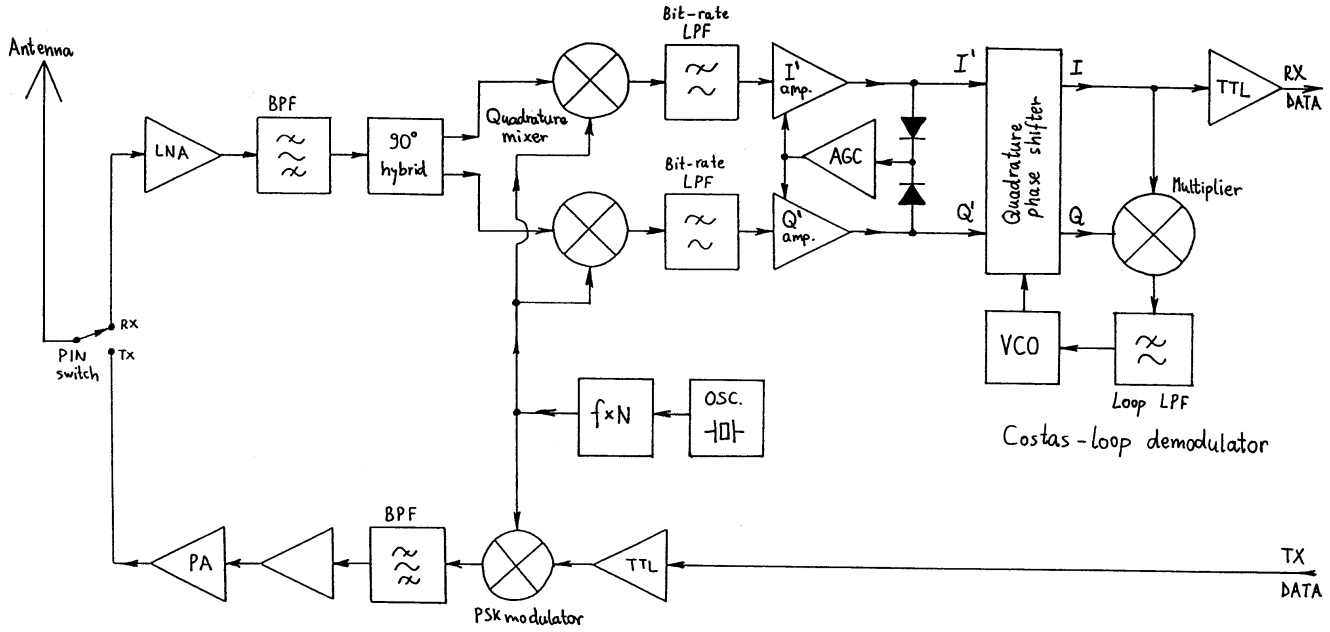


Fig. 2 - Zero-IF PSK data transceiver.

Most of the problems of a direct-conversion PSK receiver can be overcome in a so called "zero-IF" PSK receiver, as shown on fig.2. Incidentally, a zero-IF PSK transceiver requires very similar hardware to a direct-conversion PSK transceiver. The main difference is in the local oscillator. A zero-IF PSK receiver has a fixed-frequency, free-running local oscillator, while the demodulation is only performed after the main receiver gain stages.

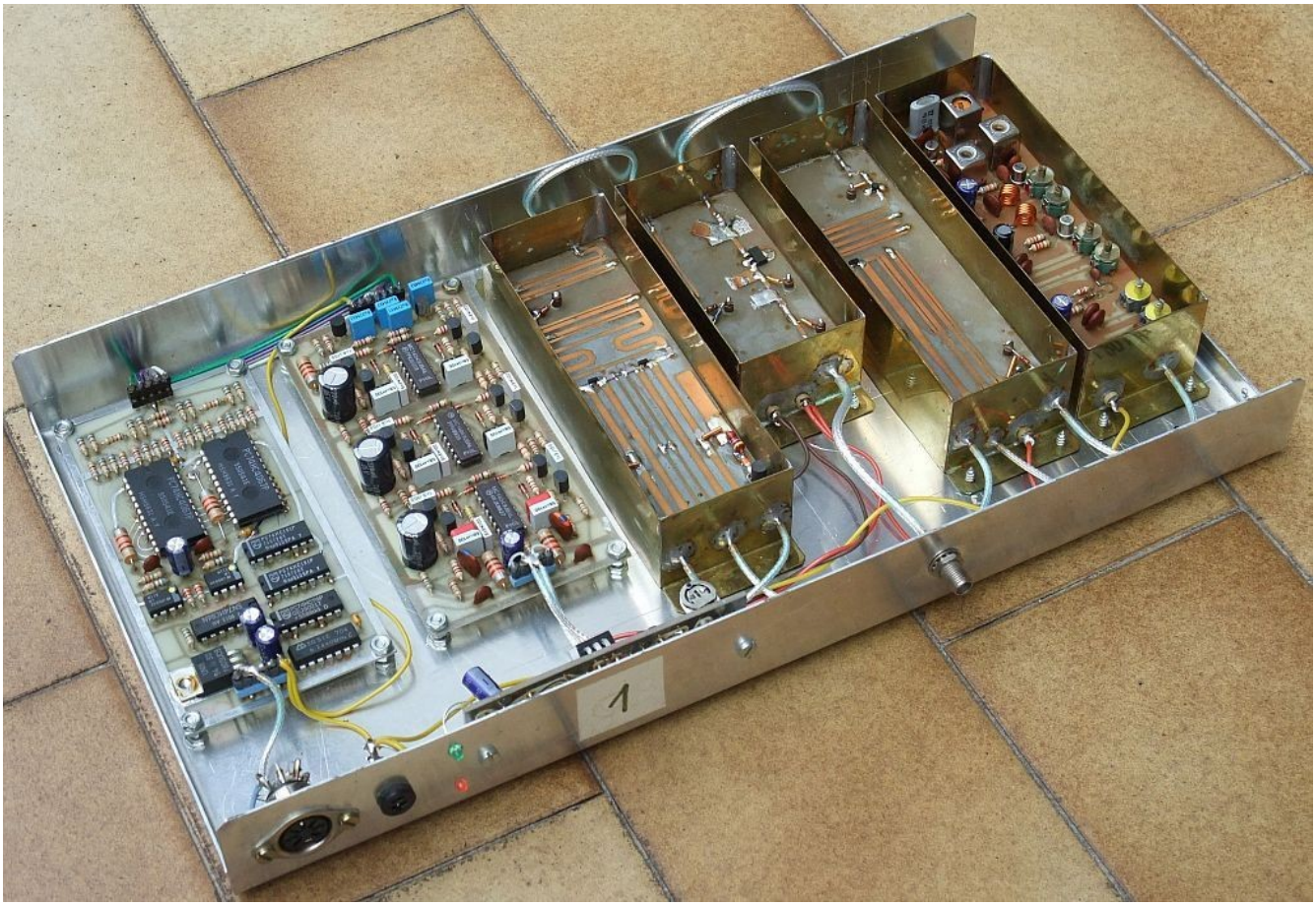
A zero-IF PSK receiver includes a quadrature mixer that provides two output signals I' and Q' with the same bandwidth as in a direct-conversion RX. The signals I' and Q' contain all of the information of the input RF signal, but they do not represent the demodulated signal yet. Since the zero-IF RX contains a free-running LO, its phase is certainly not matched to the transmitter. Further, if there is a difference between the frequencies of the transmitter and of the receiver, the phasor represented by the I' and Q' signals will rotate at a rate corresponding to the difference of the two frequencies.

To demodulate the information, the I' and Q' signals have to be fed to a phase shifter to counter-rotate the phasor. The phase shifter is kept synchronized to the correct phase and rate by a Costas-loop feedback. Since the whole Costas-loop demodulator operates at high signal levels and at relatively low frequencies, it can be built with inexpensive 74HCxxx logic circuits that require no tuning at all!

A zero-IF PSK receiver requires linear amplification of the I' and Q' signals. Limiting of the I' and Q' signals is very harmful to the overall signal-to-noise ratio. If the zero-IF amplifiers are AC coupled, data randomization (scrambling) is required. On the other hand, a zero-IF PSK transceiver does not include any critical stages or unstable feedback loops and is therefore easily reproducible.

Searching for a simple PSK transceiver design I attempted to build both a direct-conversion and a zero-IF PSK transceiver for 23cm. The 23cm band offers sufficient bandwidth for 1.2Mbit/s operation. Further, the whole transceiver can be built on conventional, inexpensive glass-fiber-epoxy laminate FR4. Finally, the propagation losses without optical visibility are smaller in the 23cm band than at higher microwave frequencies.

A direct-conversion PSK transceiver for 23cm resulted very simple. The signal and error amplifiers used just one LM311 voltage comparator each, operating as a limiting amplifier. The only limitation of this transceiver was the VCXO. Due to the undefined dynamic response of the VCXO, the capturing range of the Costas-loop RX was only about +/-5kHz. Further, even this figure was hardly reproducible, since even two crystals from the same manufacturing batch had a quite different dynamic response in the VCXO.



A zero-IF 23cm PSK transceiver resulted slightly more complex, due to the linear IF amplification with AGC and the additional Costas-loop demodulator. On the other hand, the zero-IF 23cm PSK RTX resulted fully reproducible, since there are no critical parts or unstable circuits built in. Since the additional complexity of the zero-IF RTX is in the IF part, using only cheap components and no tuning points, it does not add much to the overall complexity of the transceiver.

3. Design of the zero-IF 23cm PSK transceiver

In this article I am therefore going to describe the above-mentioned successful design of a zero-IF PSK data transceiver. The transceiver is built on seven printed-circuit boards, four of which (the RF part) are installed in metal shielded enclosures. The RF part is built mainly as micro-strip circuits on 0.8mm thick glass-fiber-epoxy laminate FR4.

Subharmonic mixers are used both in the transmitter modulator and in the receiver quadrature mixer. Subharmonic mixers with two anti-parallel diodes are simple to build. Since the LO signal is at half of the RF frequency, RF signals are easier to decouple and less shielding is required. Finally, it is very easy to build two identical subharmonic mixers for the receiver quadrature mixer.

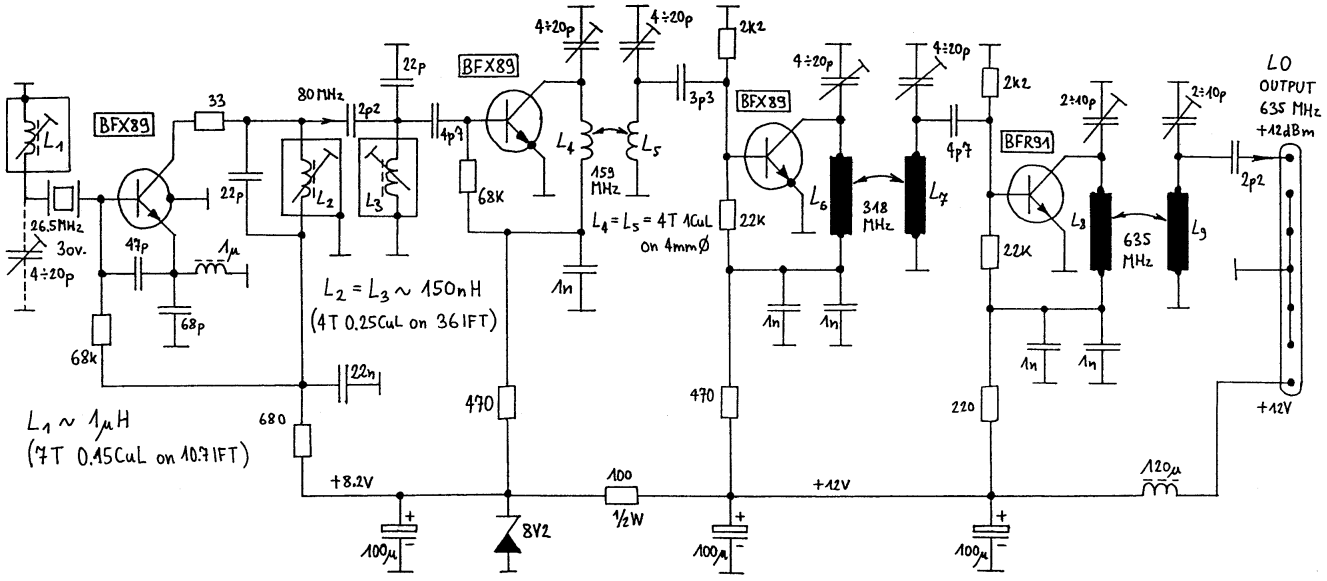


Fig. 3 – 635 MHz local oscillator.

The whole transceiver therefore requires a single local oscillator operating at half of the RF frequency or at about 635MHz for operation in the 23cm amateur band. The local oscillator including a crystal oscillator and multiplier stages is shown on fig.3. The LO module is built on a single-sided PCB, as shown on fig.4 and fig.5.

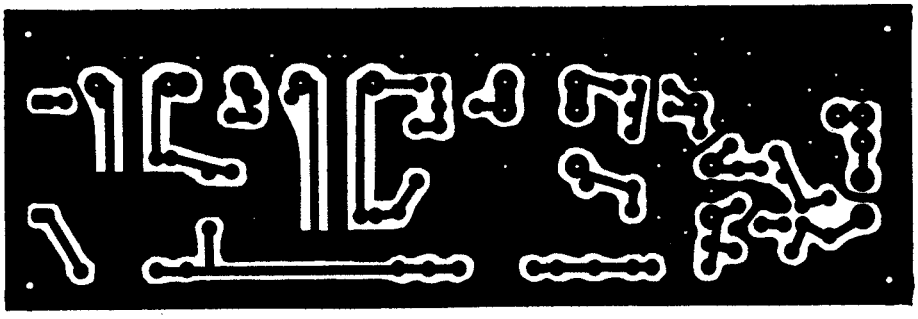


Fig. 4 - 635 MHz LO PCB (0.8mm single-sided FR4).

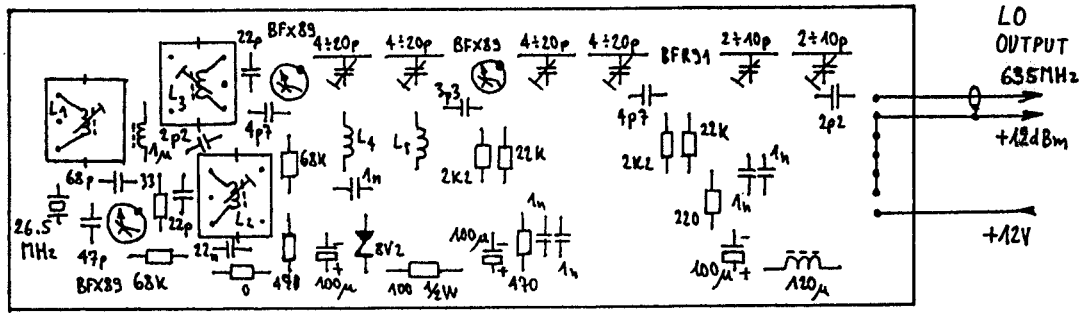


Fig. 5 - 635 MHz LO component location.

To speed-up the TX/RX switching, the receiving mixers are powered on and are receiving the LO signal all of the time. On the other hand, the LO signal feeding the modulator has to be turned off to avoid any interference during reception. Therefore the LO signal is fed to the receiving mixers through a directional coupler located in the 1270MHz PSK modulator module as shown on fig.6.

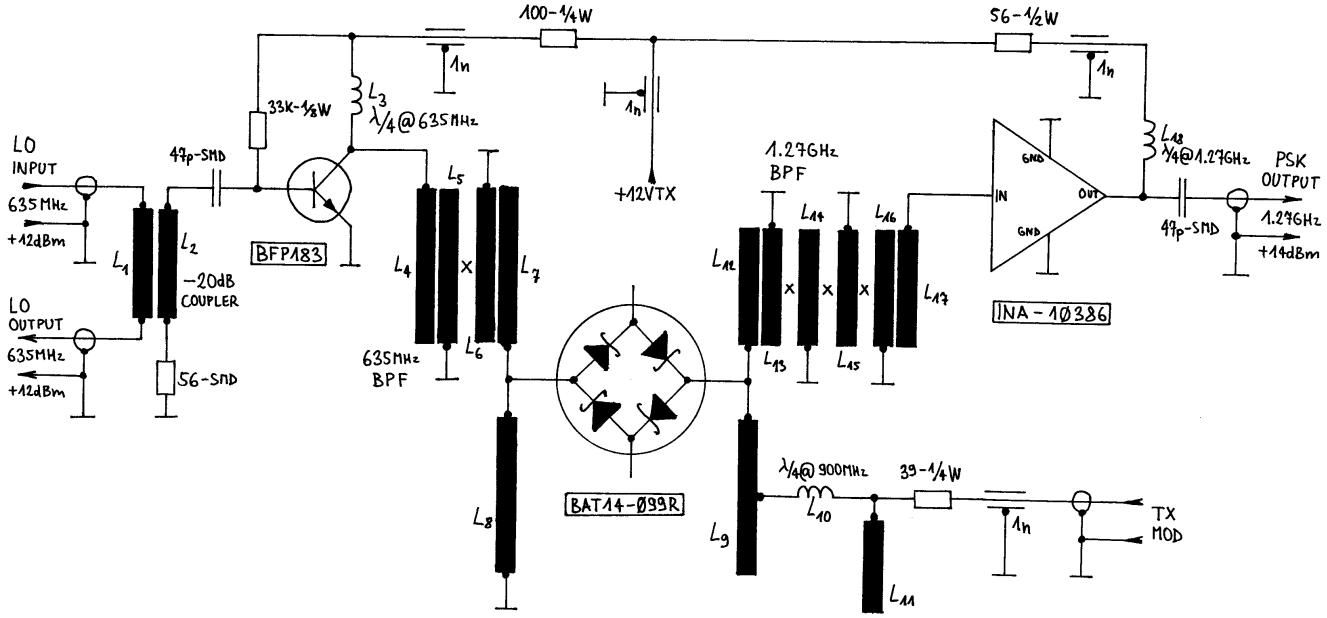


Fig. 6 - 1270MHz PSK modulator.

Only a small fraction of the LO power (-20dB) is fed to a separation amplifier stage (BFP183). The 635MHz BPF ensures a good residual carrier suppression (>30dB) in the PSK modulator. The 1.27GHz BPF is used to suppress the 635MHz LO signal and its unwanted harmonics. Finally, a two-stage MMIC amplifier (INA-10386) is used to boost the signal level to +14dBm.

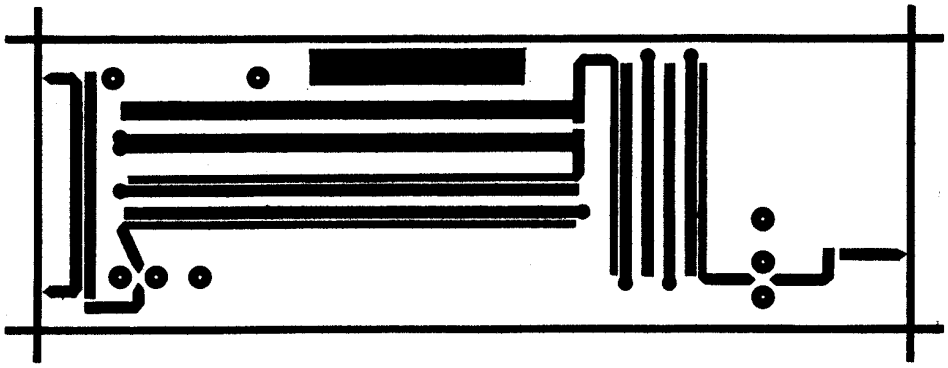


Fig. 7 - 1270 MHz PSK modulator PCB (0.8mm double-sided FR4).

The 1270MHz PSK modulator is a micro-strip circuit built on a double-sided PCB as shown on fig.7 and fig.8. The bottom side of the PCB is not etched to serve as a ground-plane for the micro-strip circuit. The RF signal losses in the FR4 laminate are rather high at 1.27GHz. For example, the 1.27GHz BPF has a pass-band

insertion loss of about 5dB. On the other hand, all of the micro-strip bandpass filters are designed for a bandwidth of more than 10% of the center frequency and therefore require no tuning considering the laminate and etching tolerances.

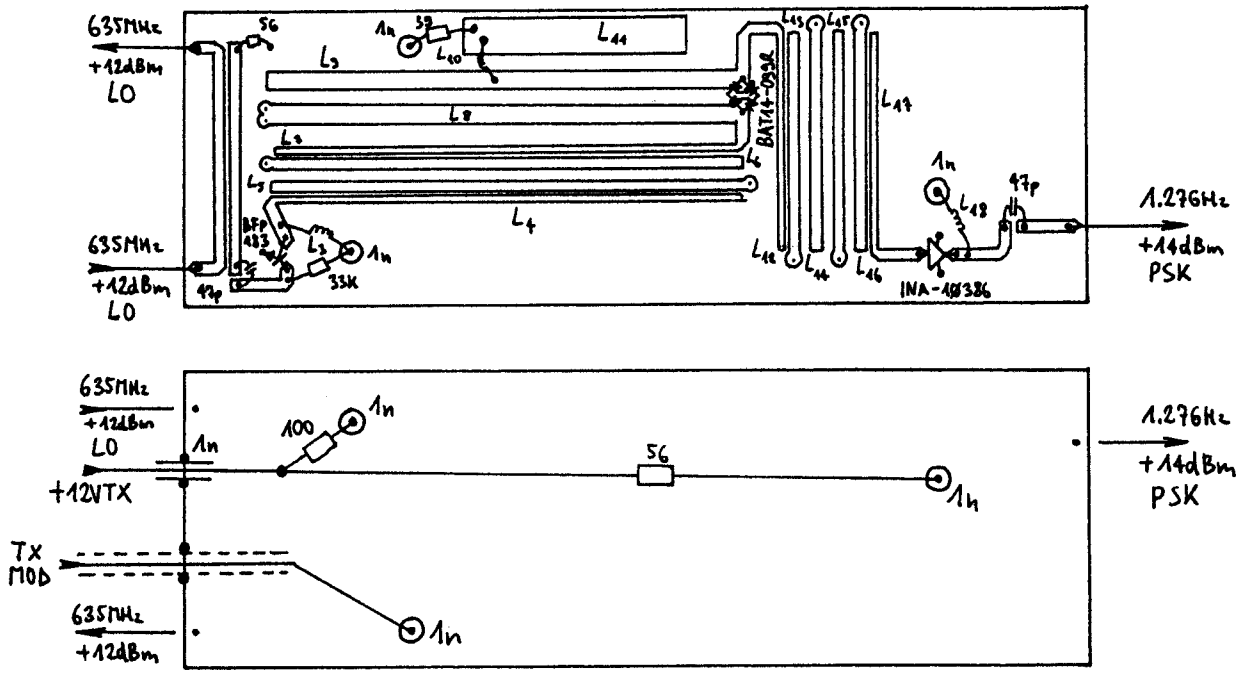
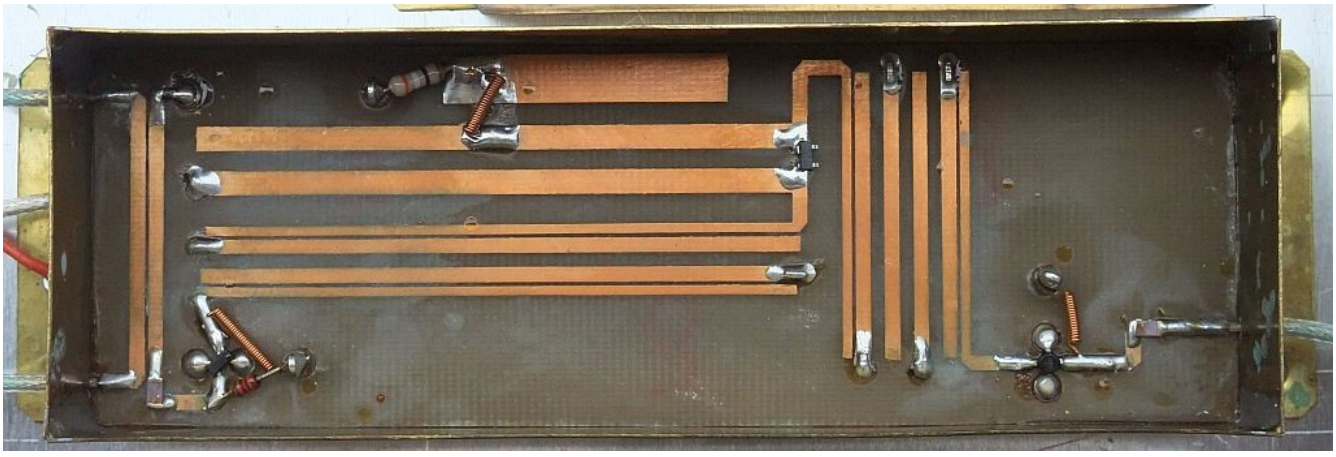


Fig. 8 - 1270 MHz PSK modulator component location.



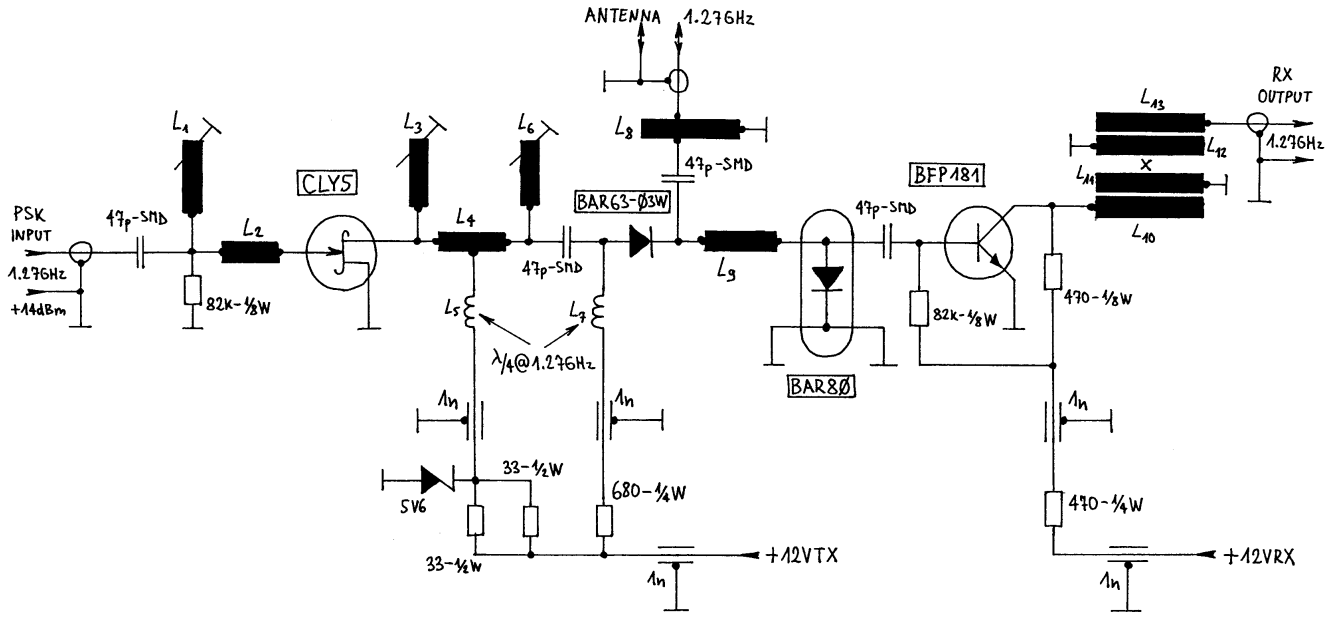


Fig. 9 - 23cm PSK transceiver, RF front-end.

The RF front-end of the 23cm PSK transceiver, shown on fig.9, includes a TX power amplifier with a CLY5 power GaAsFET to boost the TX output power to about 1W (+30dBm), a PIN diode antenna switch (BAR63-03W and BAR80) and a receiving RF amplifier with a BFP181. The latter has about 15dB gain, but the following 1.27GHz BPF has about 3dB pass-band loss. The RF front-end is also built as a micro-strip circuit on a double-sided PCB as shown on fig.10 and fig.11.

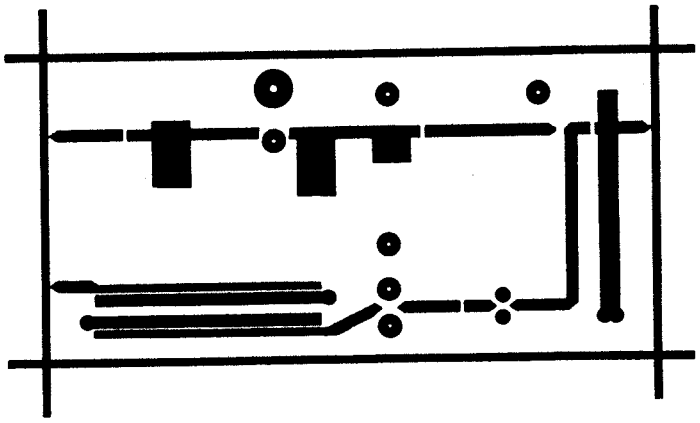


Fig. 10 - RF front-end PCB (0.8mm double-sided FR4).

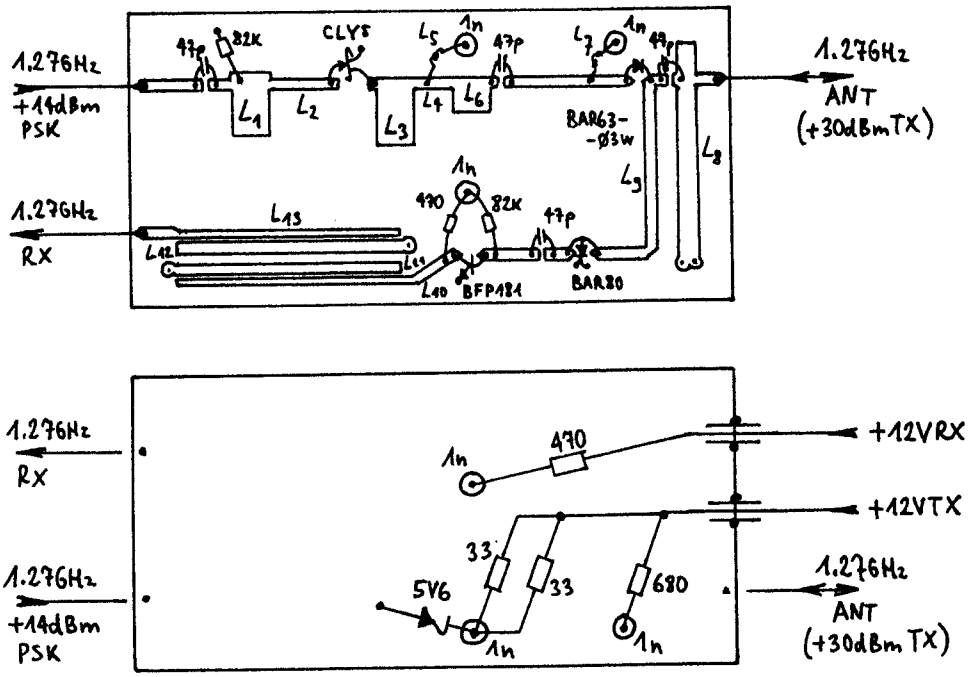
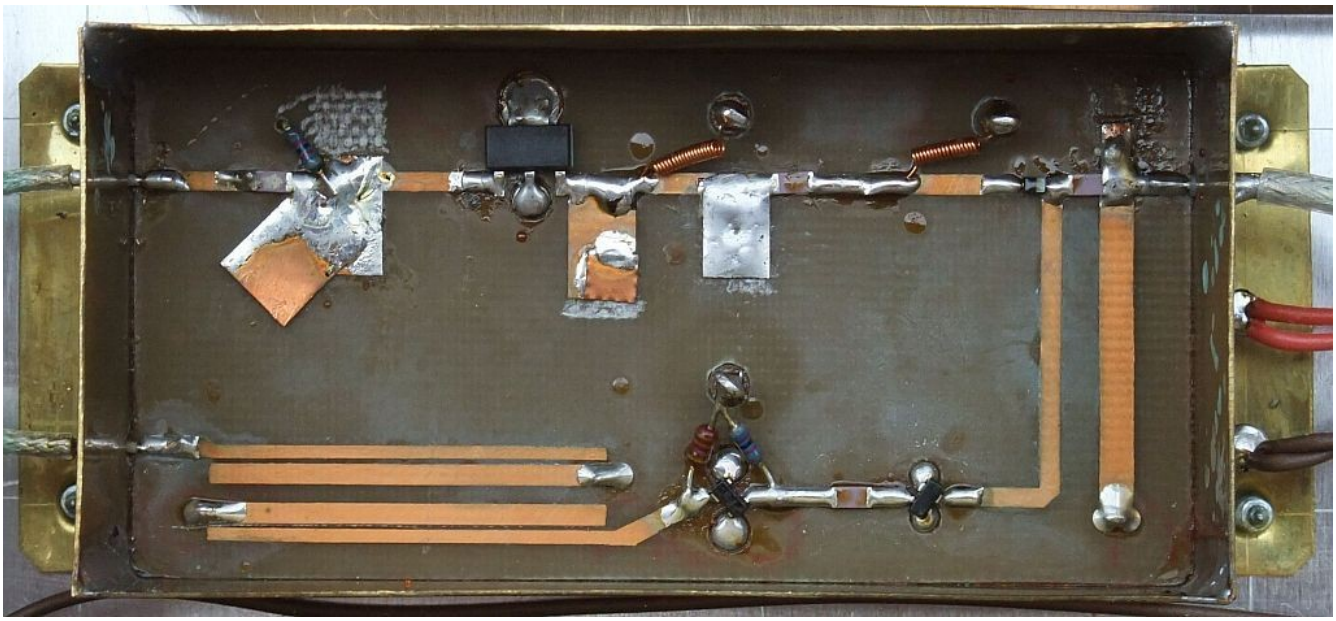


Fig. 11 - RF front-end component location.



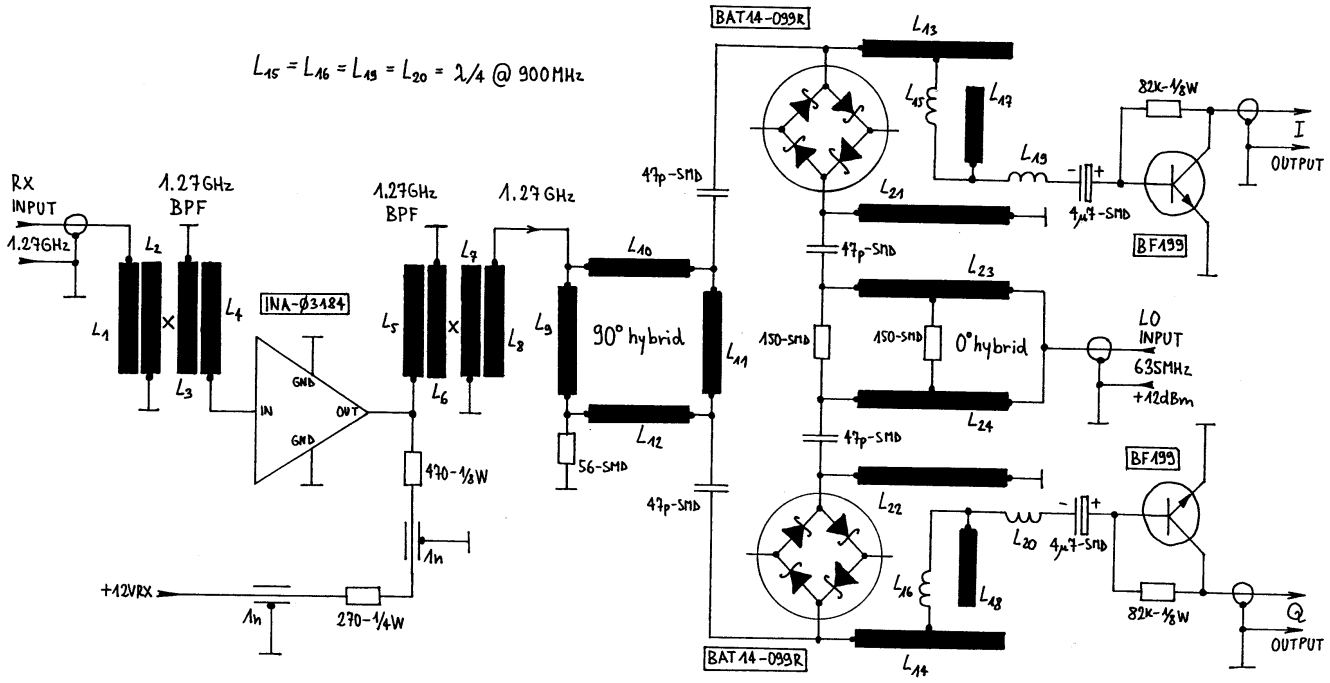


Fig. 12 - Quadrature I/Q mixer for 1270MHz.

The quadrature I/Q mixer for 1270MHz, shown on fig.12, includes an additional gain stage at 1.27GHz (26dB MMIC INA-03184), two bandpass filters at 1.27GHz (3dB insertion loss each), a quadrature hybrid for the RF signal at 1.27GHz, an in-phase power splitter for the LO signal at 635MHz, two identical subharmonic mixers (two BAT14-099R schottky quads) and two identical IF preamplifiers (two BF199).

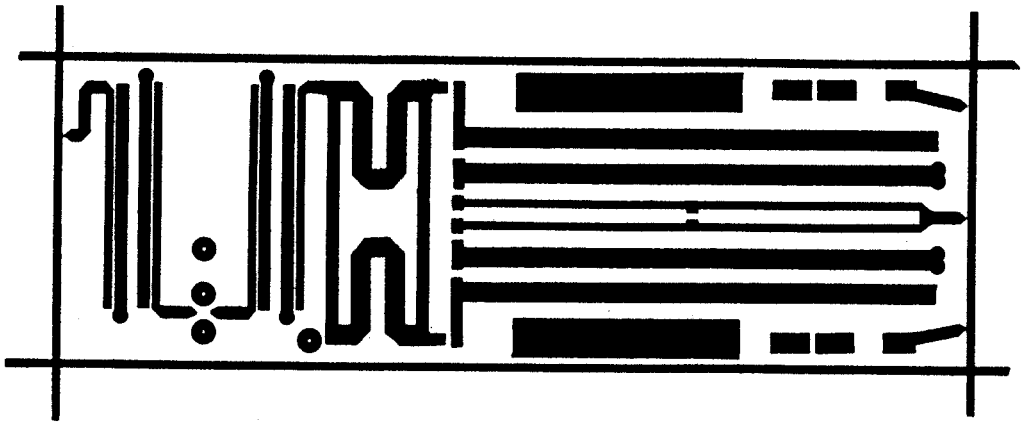


Fig. 13 - Quadrature mixer PCB (0.8mm double-sided FR4).

Since the termination impedances of the subharmonic mixers depend on the LO signal power, the difference ports of both the quadrature (RF) and in-phase (LO) power splitters have to be terminated to ensure the correct phase and amplitude relationships. Considering the manufacturing tolerances of the micro-strip PCB shown on fig.13 and fig.14, the amplitude matching is usually within 5% and the phase shift is within +/-5degrees from the nominal 90degrees.

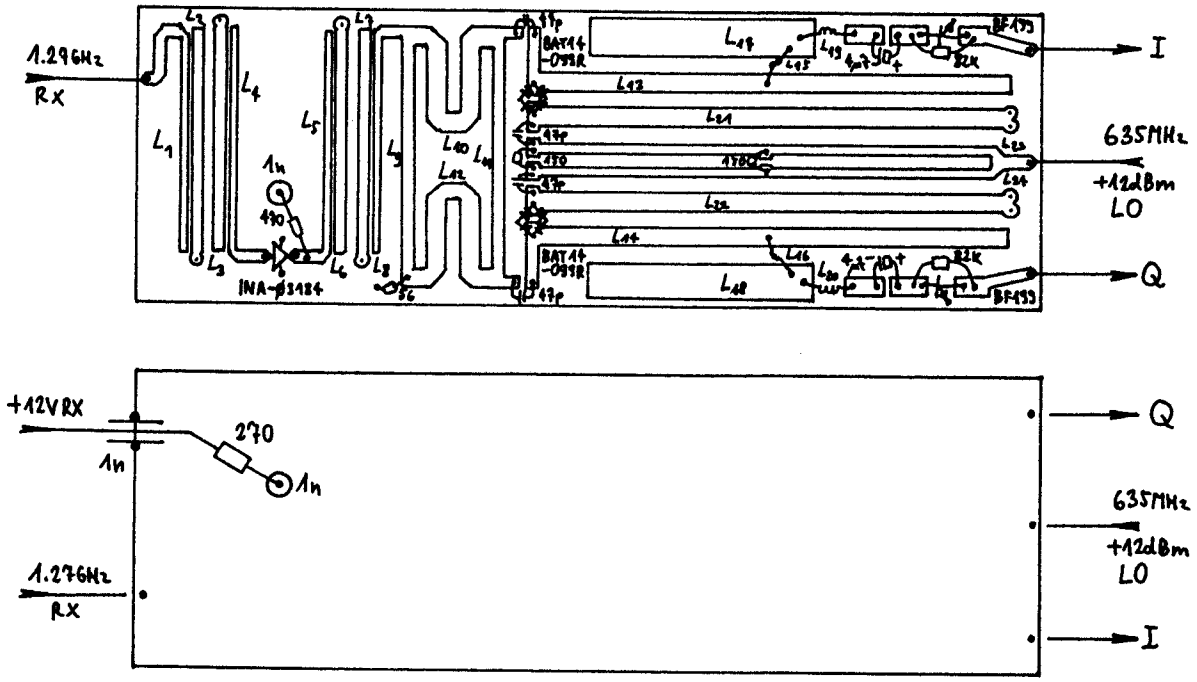
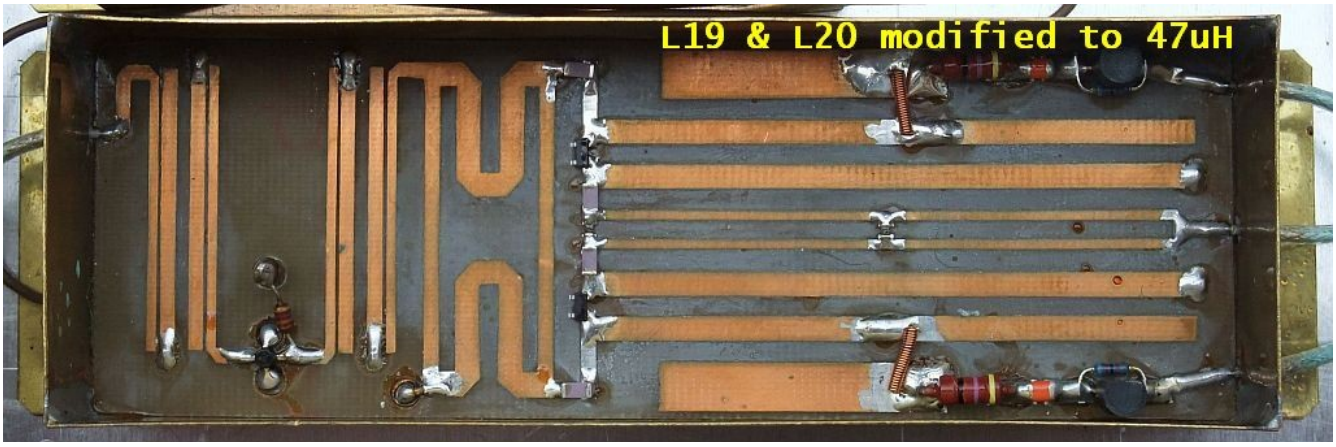


Fig. 14 - Quadrature mixer component location.



A zero-IF receiver requires a dual IF amplifier with two identical amplification channels, but a single, common AGC. Since DC-coupled amplifiers can not be built, the lower frequency limit of AC-coupled stages has to be set sufficiently low. At a data rate of 1.2Mbit/s, a convenient choice is a lower frequency limit of 1kHz. The latter allows all of the time constants in the range of 1ms (TX/RX switching time!) and causes a distortion of about 4% of the amplitude of the IF signal.

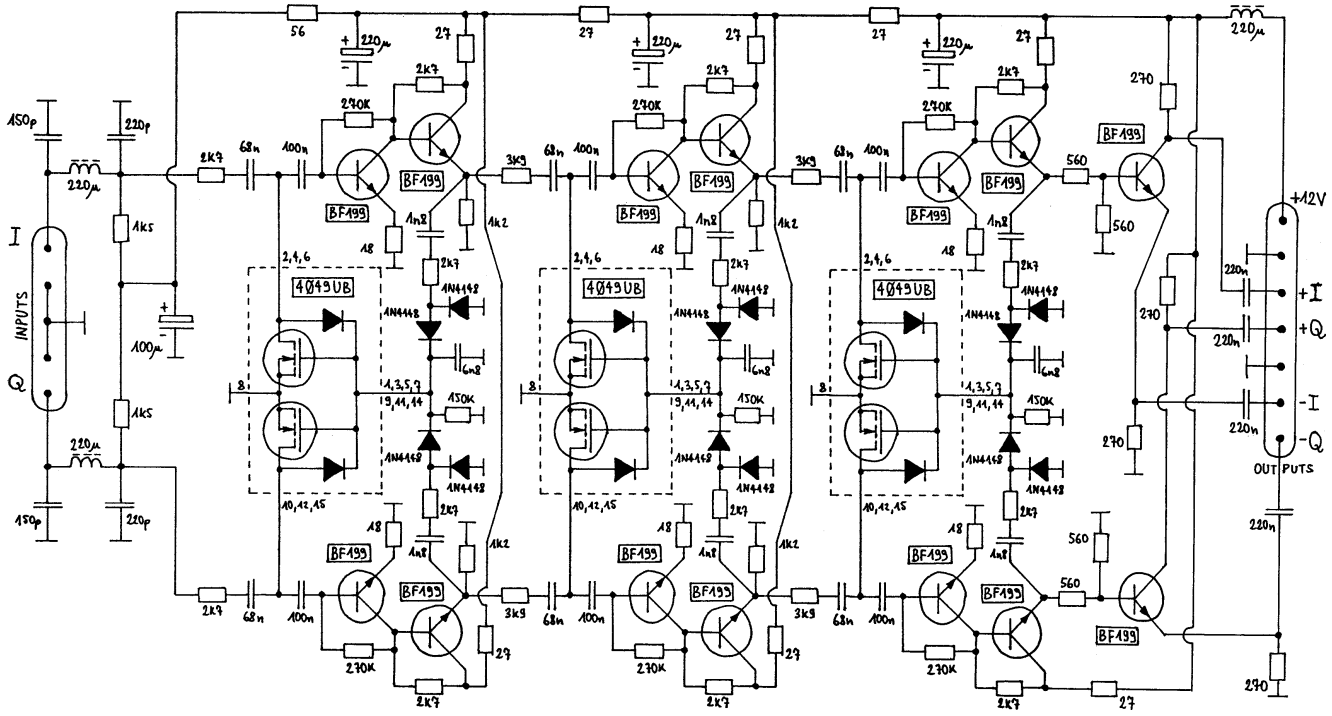


Fig. 15 - I/Q dual amplifier with common AGC stages.

Of course the AGC time constant should also be in the same range around 1ms. Such a fast AGC can only be applied to low gain stages to avoid unwanted feedback. A simple technical solution is to use more than one AGC in the IF amplifier chain. The I/Q dual amplifier shown on fig.15 has three identical dual amplifier stages and each of these dual stages has its own AGC circuit using MOS transistors (4049UB) as variable resistors.

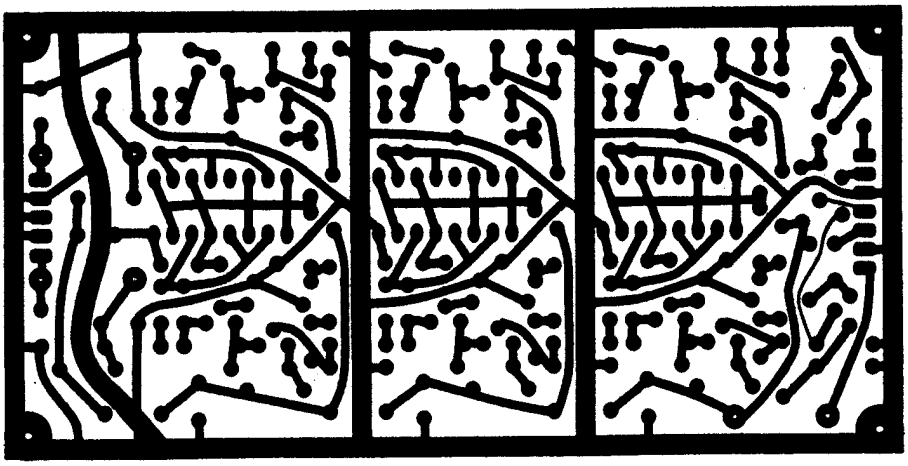


Fig. 16 - I/Q dual amplifier PCB (1.6mm single-sided FR4).

The I/Q dual amplifier module also includes two identical low-pass filters on the input (that define the receiver bandwidth) and two phase inversion stages on the output to obtain a four-phase output signal (+I, +Q, -I and -Q) to drive the following phase shifter. The I/Q dual amplifier is built on a single-sided PCB as shown on fig.16 and fig.17.

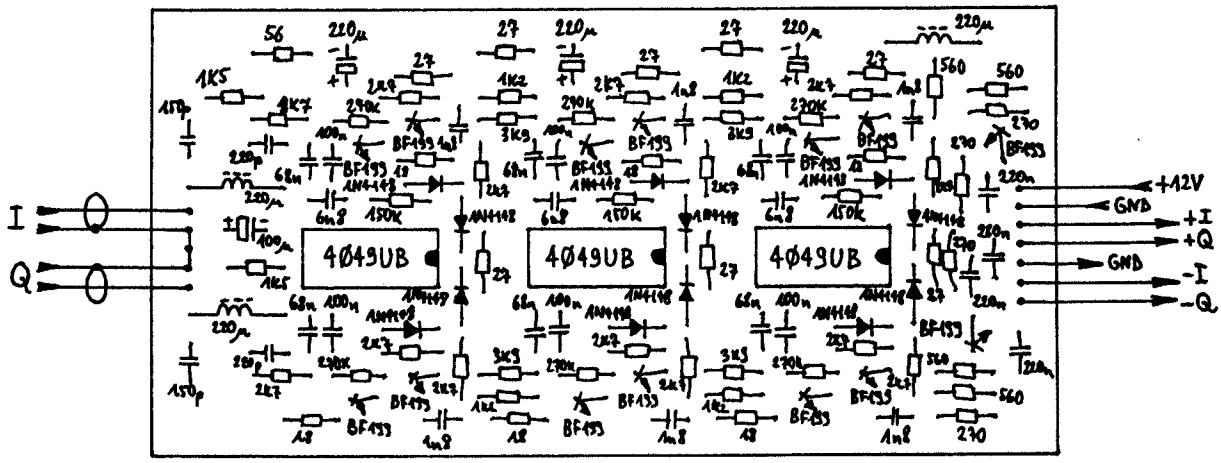
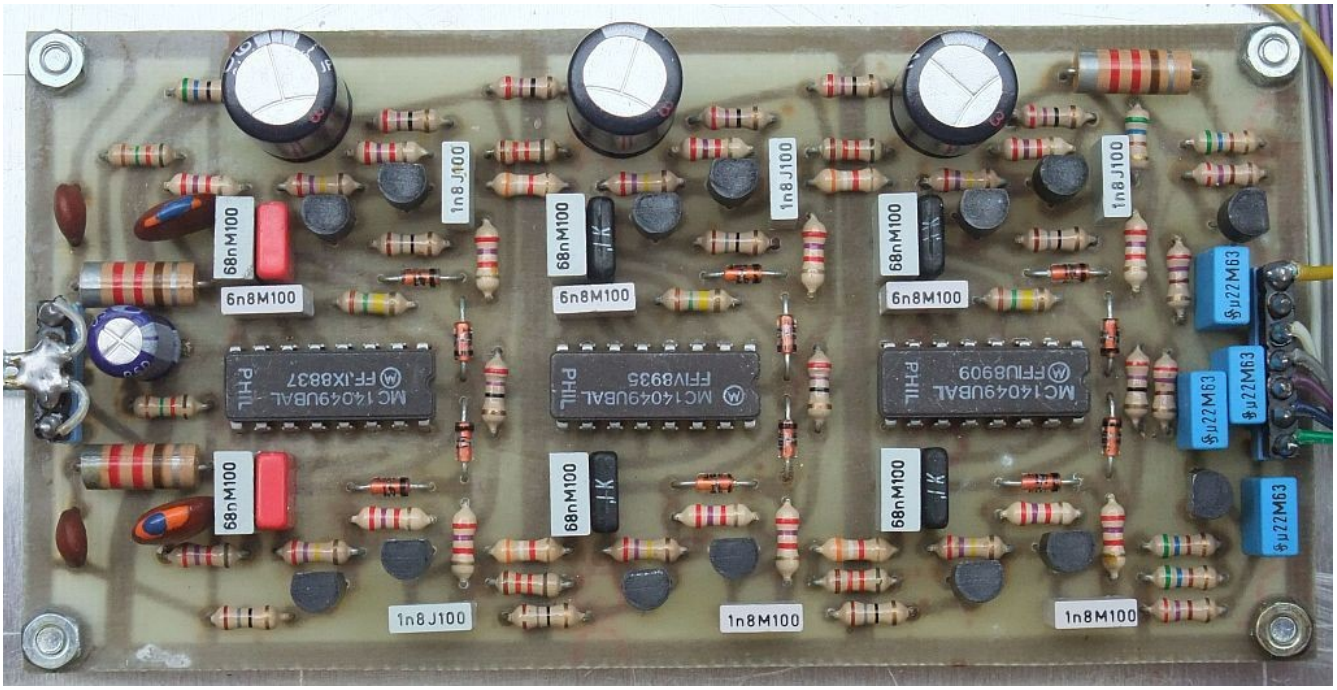


Fig. 17 - I/Q dual amplifier component location.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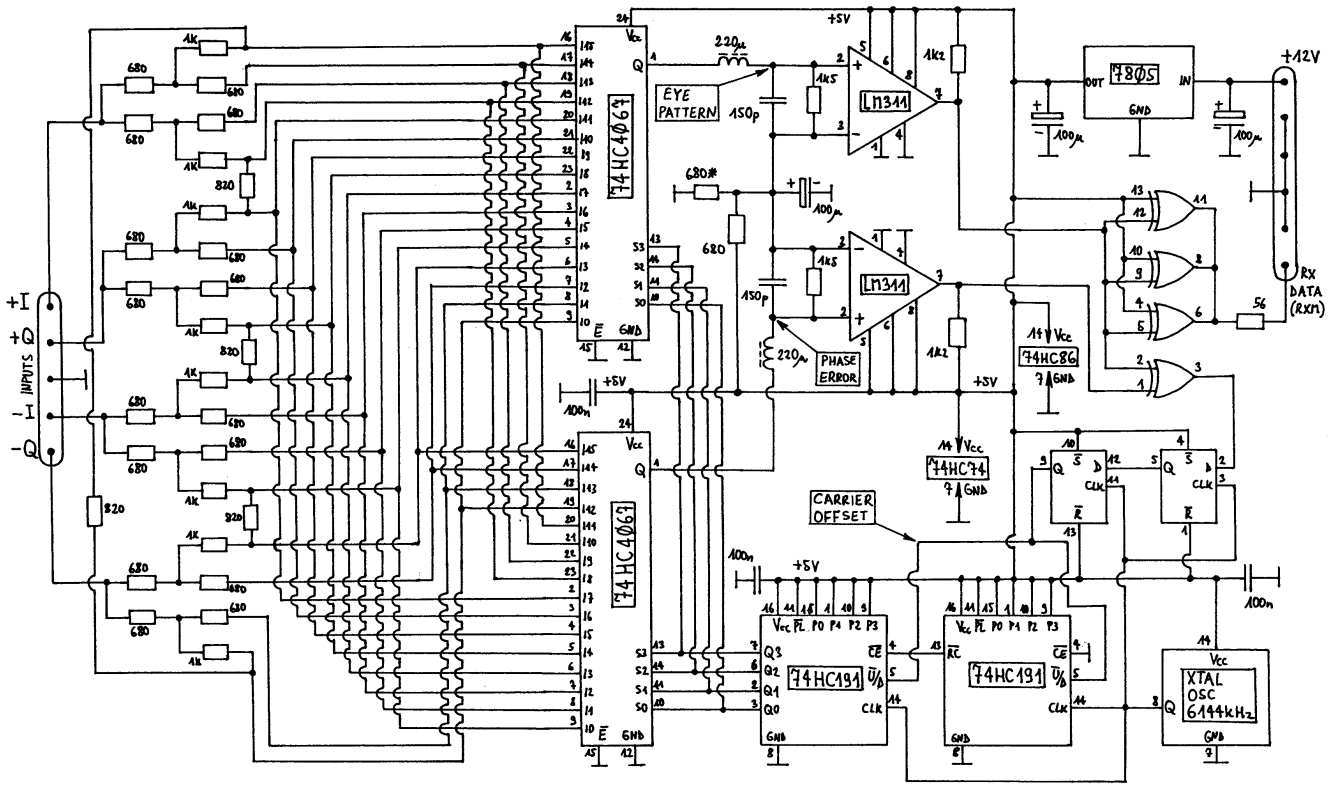


Fig. 18 - Costas-loop I/Q PSK demodulator.

The Costas-loop I/Q PSK demodulator is built entirely using cheap 74HCxxx logic as shown on fig.18. The four-phase input signal (+I, +Q, -I and -Q) feeds a resistor network that generates a multiphase system with a large number (16) of phases. Two 74HC4067 analog switches are then used to select the desired signal phase. The inputs of the two analog selectors are offset by 4 to provide the required 90-degree phase shift between the signal and error outputs.

Both the signal and error are first fed through two low-pass filters (to suppress the 74HC4067 switching transients) and finally to two LM311 voltage comparators to obtain TLL-level signals. The signal and error are then multiplied in an EXOR gate and feed a digital VCO. The digital VCO includes a 6.144MHz clock oscillator and two 74HC191 up/down counters.

The up/down control is used as the VCO control input. If the latter is at a logical ZERO, the up/down counter rotates the two 74HC4067 switches FORWARD with a frequency of 24kHz. If the input is at a logical ONE, the up/down counter rotates the two 74HC4067 switches BACKWARD with a frequency of 24kHz. Finally, if the control input toggles, the result depends on the ON/OFF ratio of the control signal. At 50% duty the 74HC4067 switches stay in the same position.

The overall circuit therefore operates as a first-order, Costas phase-locked loop that is able to correct carrier-frequency errors between -24kHz and +24kHz. The loop gain is defined by the dividing ratio of the 74HC191 up/down counters and the clock frequency. If a wider capturing range is desired, the clock frequency can be increased up to 20MHz, but the resulting higher loop gain also increases the phase noise!

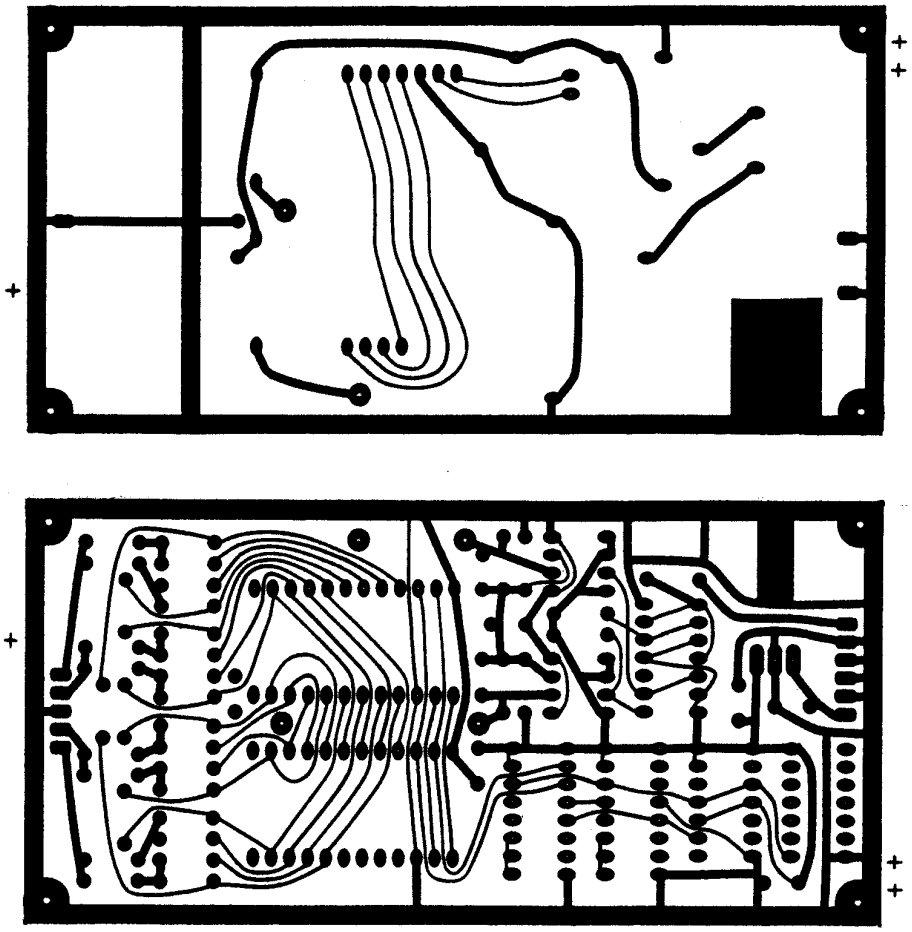


Fig. 19 - Costas-loop demodulator PCB (1.6mm double-sided FR4).

The Costas-loop demodulator is built on a double-sided PCB as shown on fig.19 and fig.20. The circuit includes its own +5V regulator and an output stage capable of feeding a 75-ohm cable with the demodulated RX data.

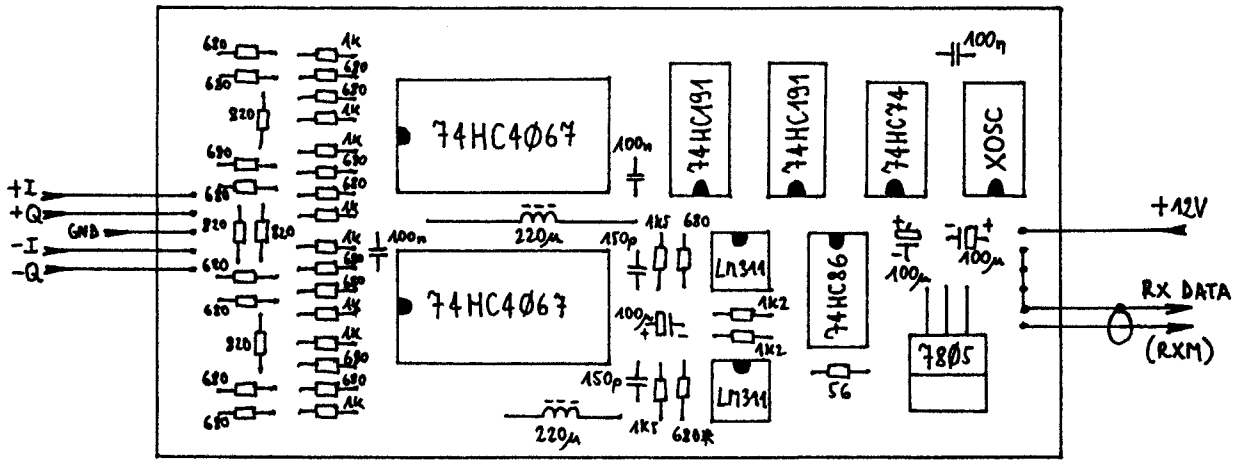
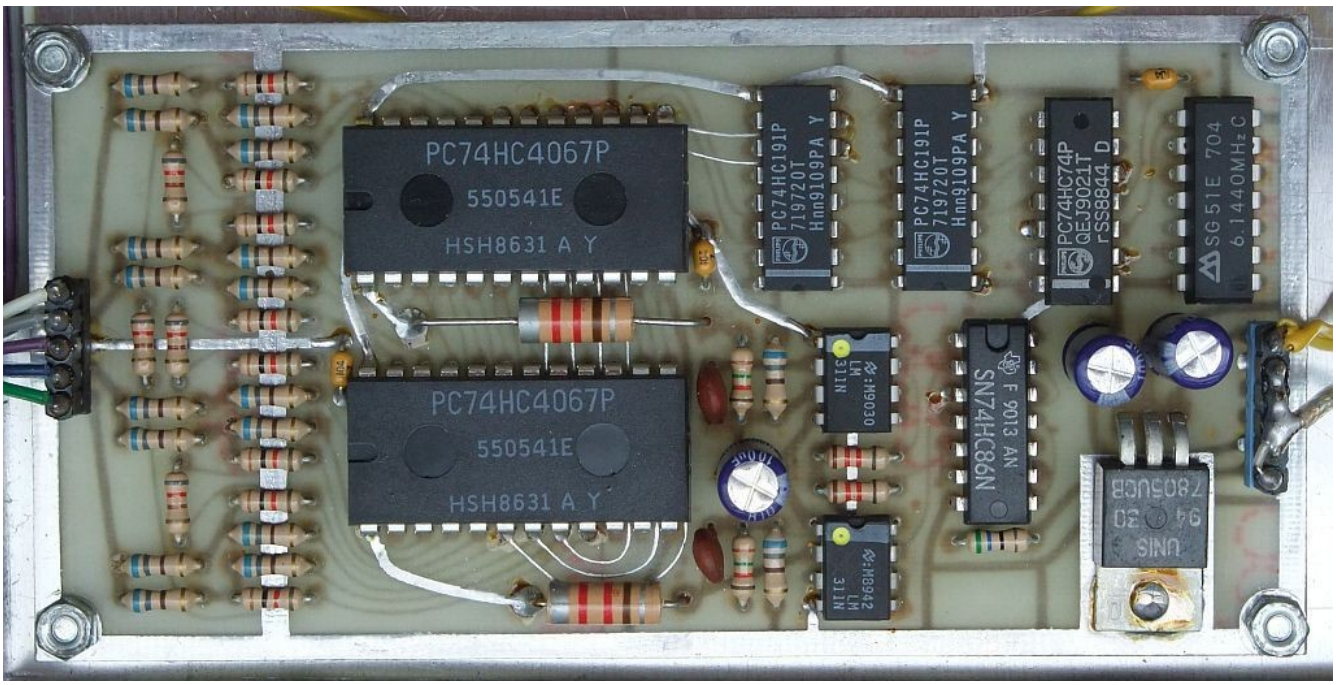


Fig. 20 - Costas-loop demodulator component location.



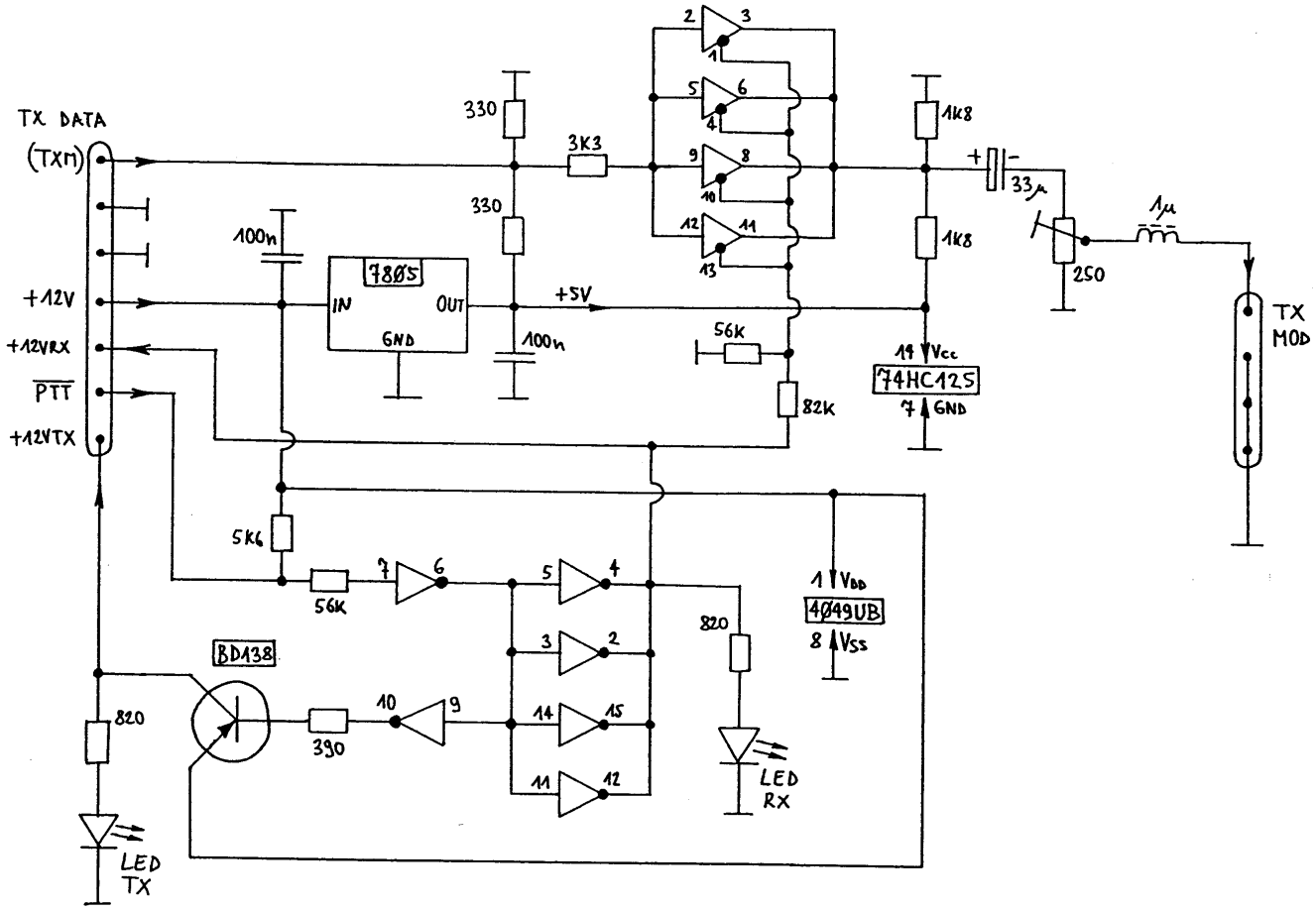


Fig. 21 - Supply switch interface circuit diagram.

The overall PSK transceiver requires a few additional interface circuits (shown on fig.21) including a supply voltage switch and a modulator driver. The modulator driver includes a low-pass filter to decrease the high-order side-lobes of the modulation spectrum. The supply switch interface is built on a single-sided PCB as shown on fig.22 and fig.23.

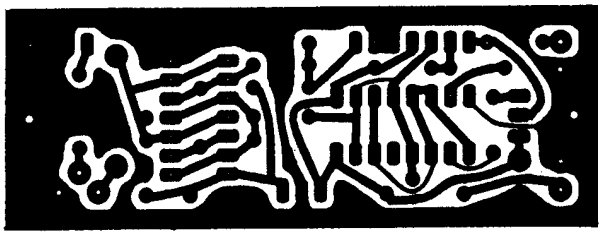


Fig. 22 - Supply switch interface PCB (1.6mm single-sided FR4).

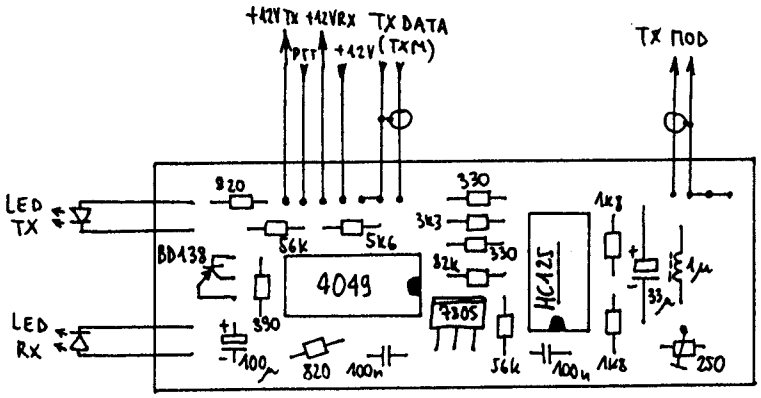
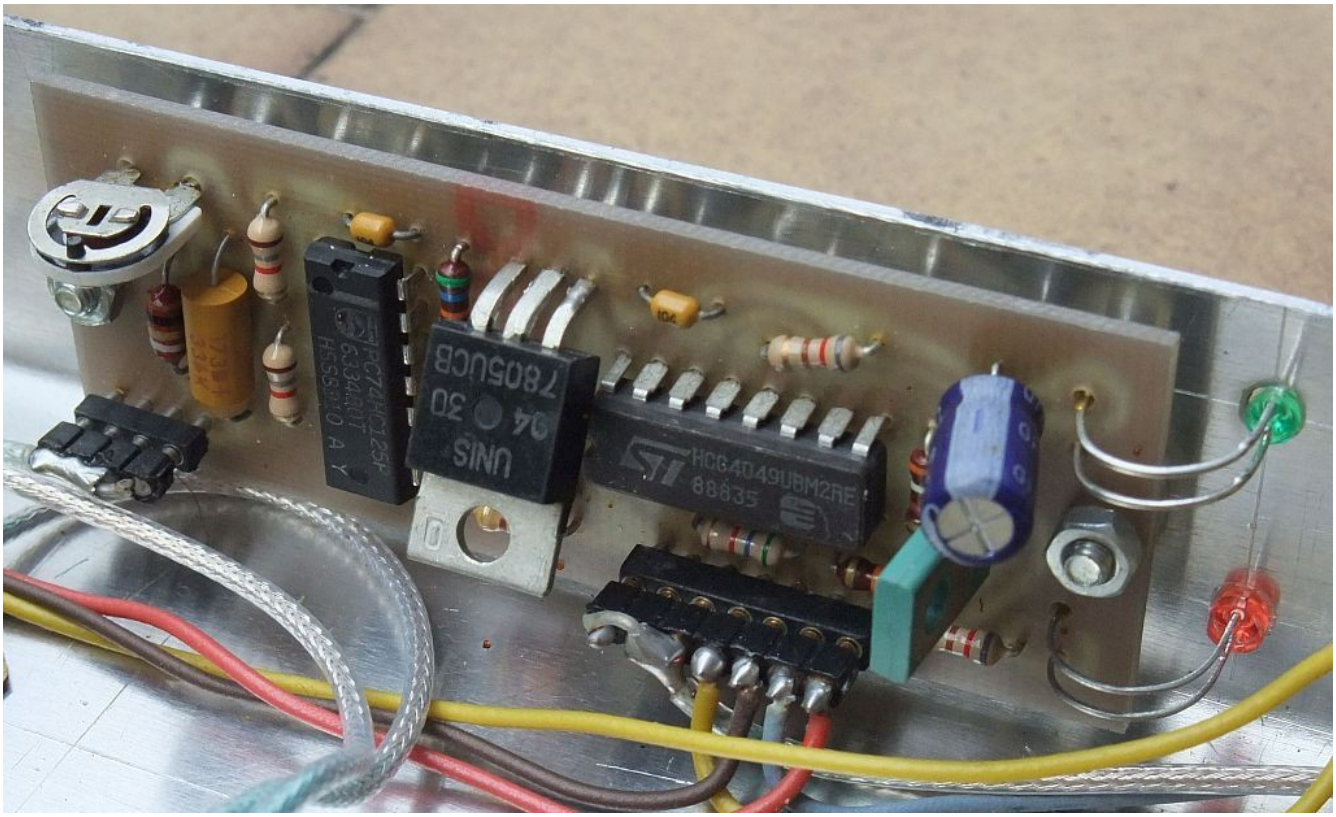
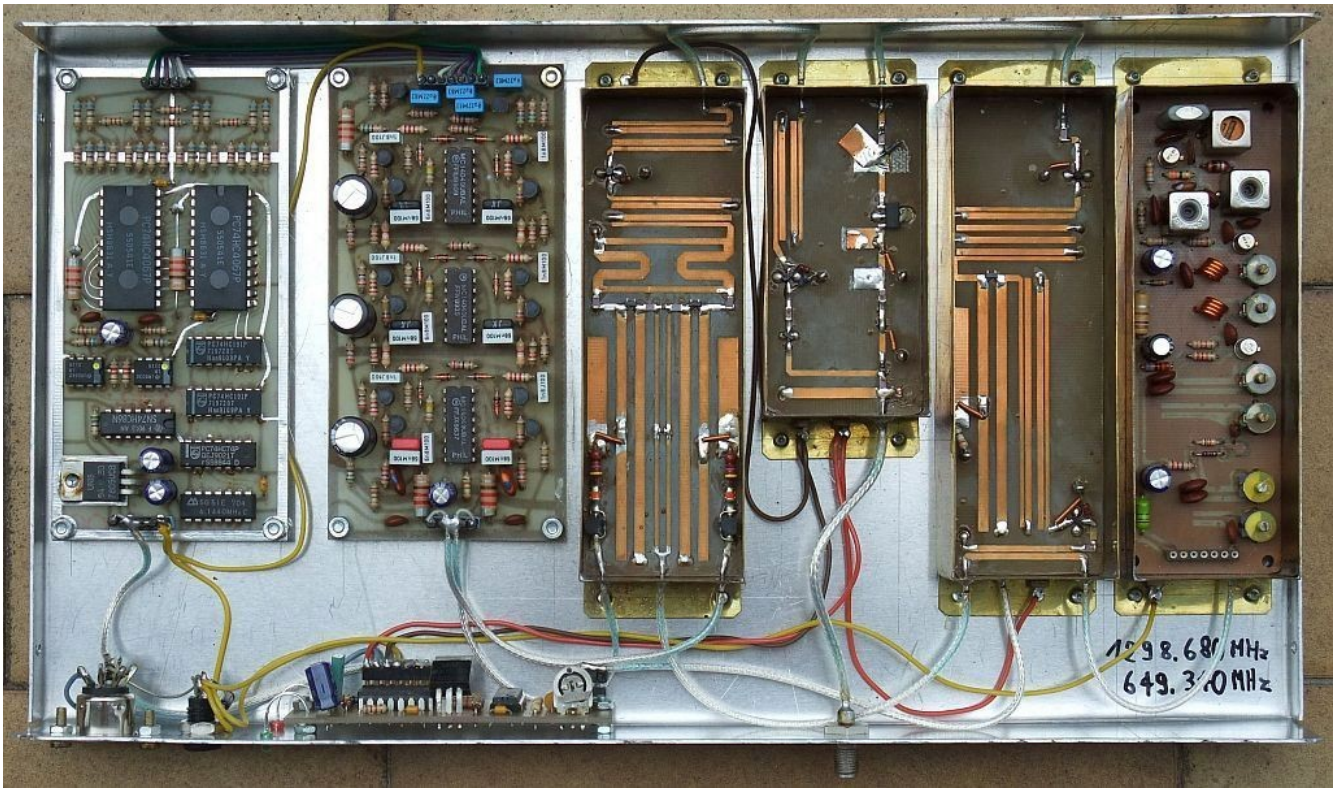


Fig. 23 – Supply switch interface component location.





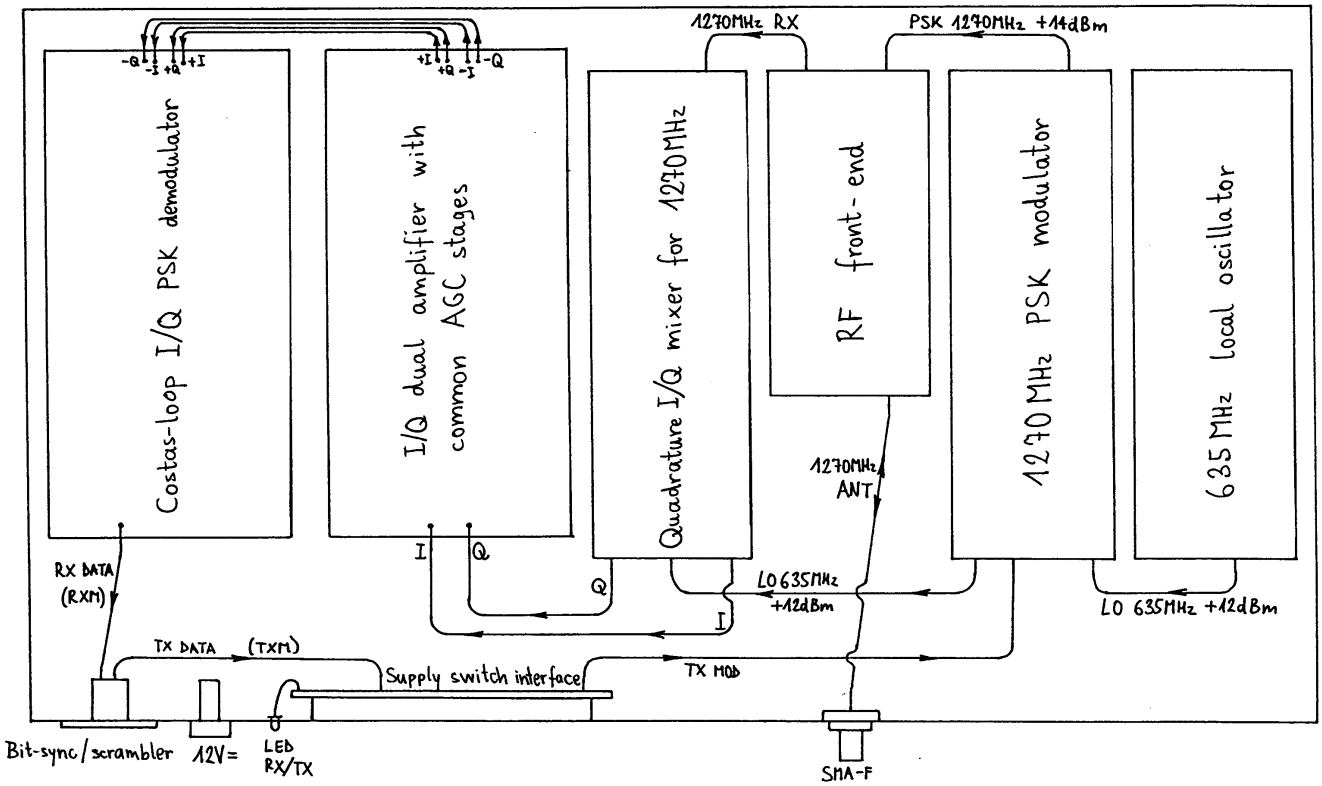
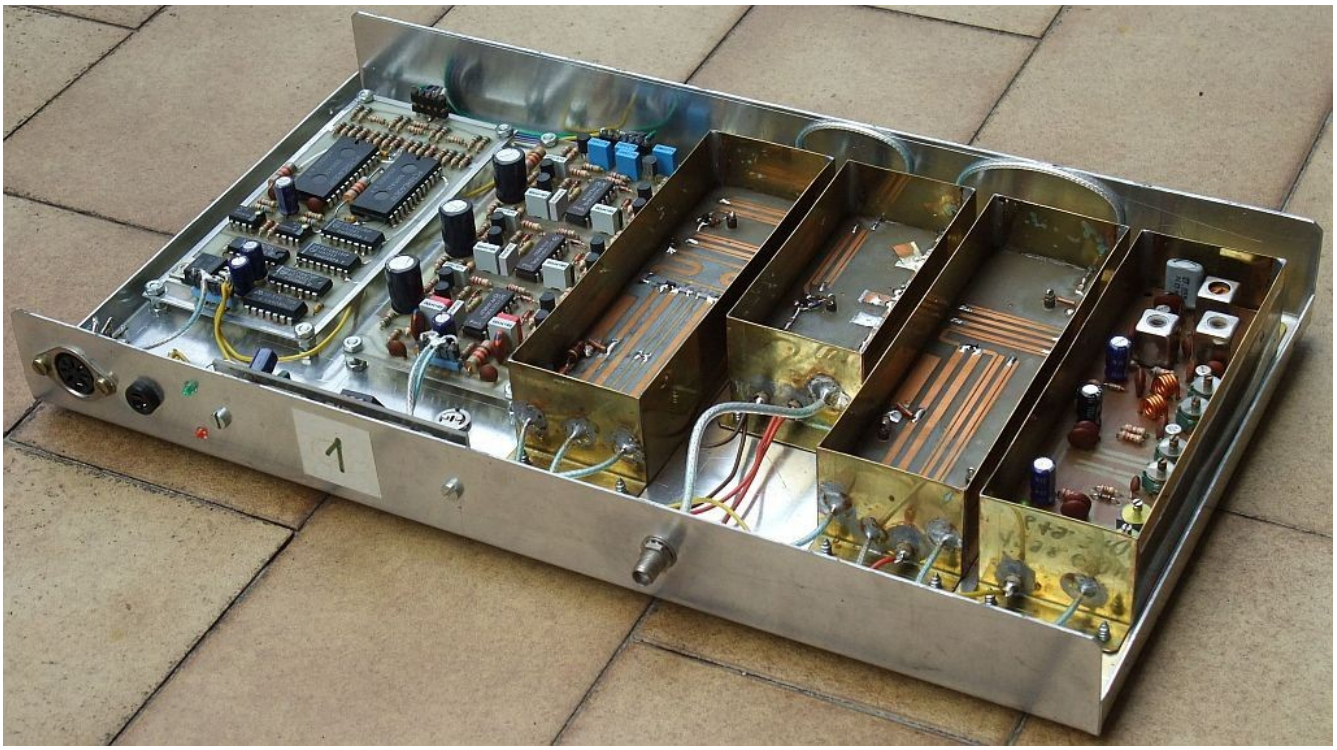
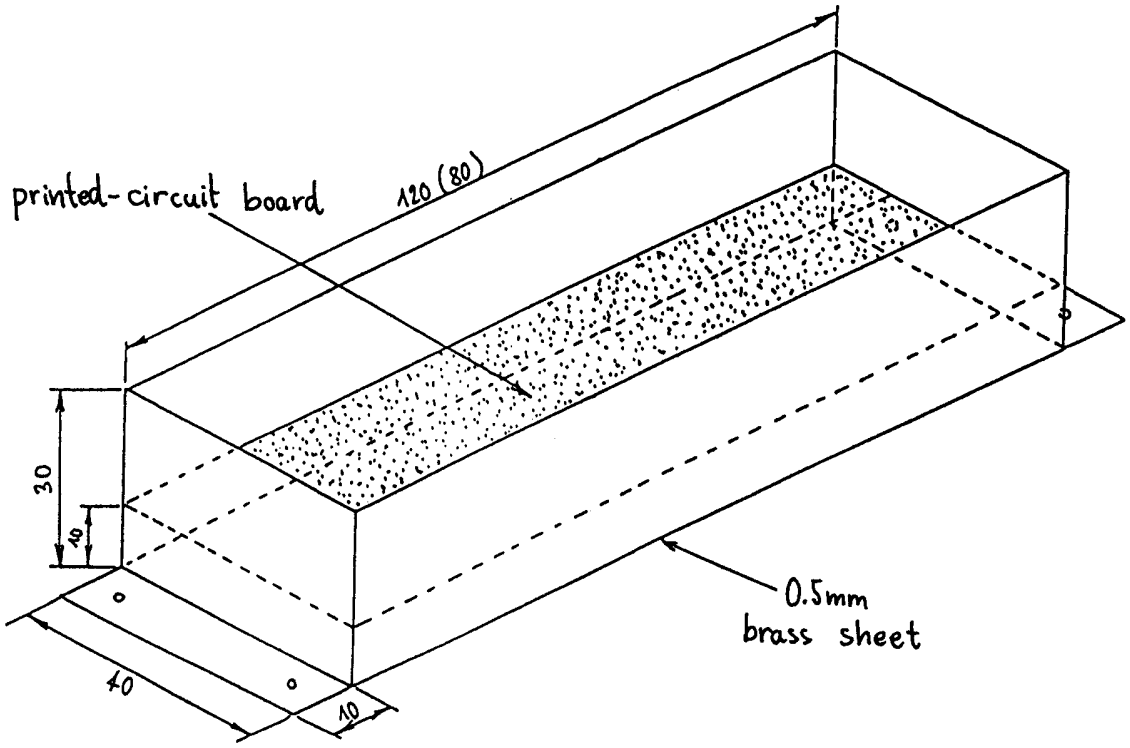


Fig. 24 - 23cm PSK transceiver module location.

The overall PSK transceiver is enclosed in an aluminum box with the

dimensions of 320mm (width) X 175mm (depth) X 32mm (height). The location of the single modules is shown on fig.24. The four RF modules are additionally shielded in small boxes made of 0.5mm thick brass sheet as shown on fig.25. The ground-plane of the PCBs is soldered along all four sides to the brass frame to ensure a good electrical contact.





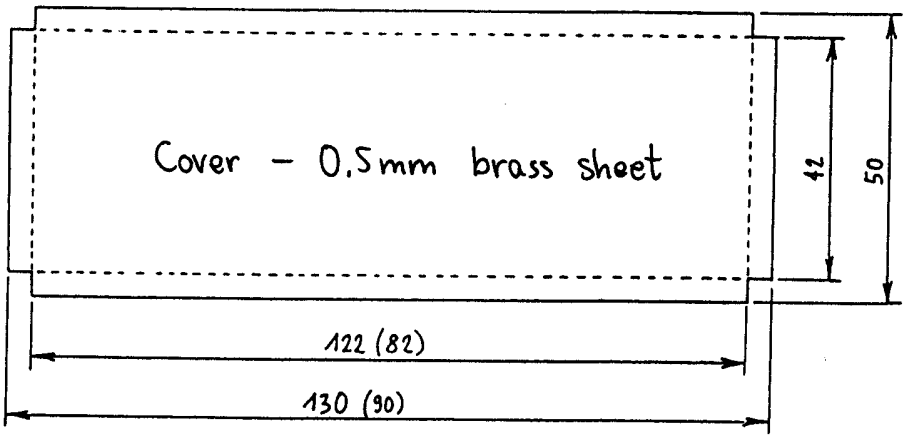


Fig. 25 - 23 cm PSK transceiver shielded module enclosure.

Special care should be devoted to the assembly of the micro-strip circuits. The micro-strip resonators are grounded at the marked positions using 0.6mm thick

CuAg wire. The SMD components (shown on fig.26) are grounded through 2.5mm, 3.2mm or 5mm diameter holes at the marked positions. The holes are first covered with a piece of thin copper sheet on the ground-plane side, then they are filled with solder and finally the SMD part is soldered in place.

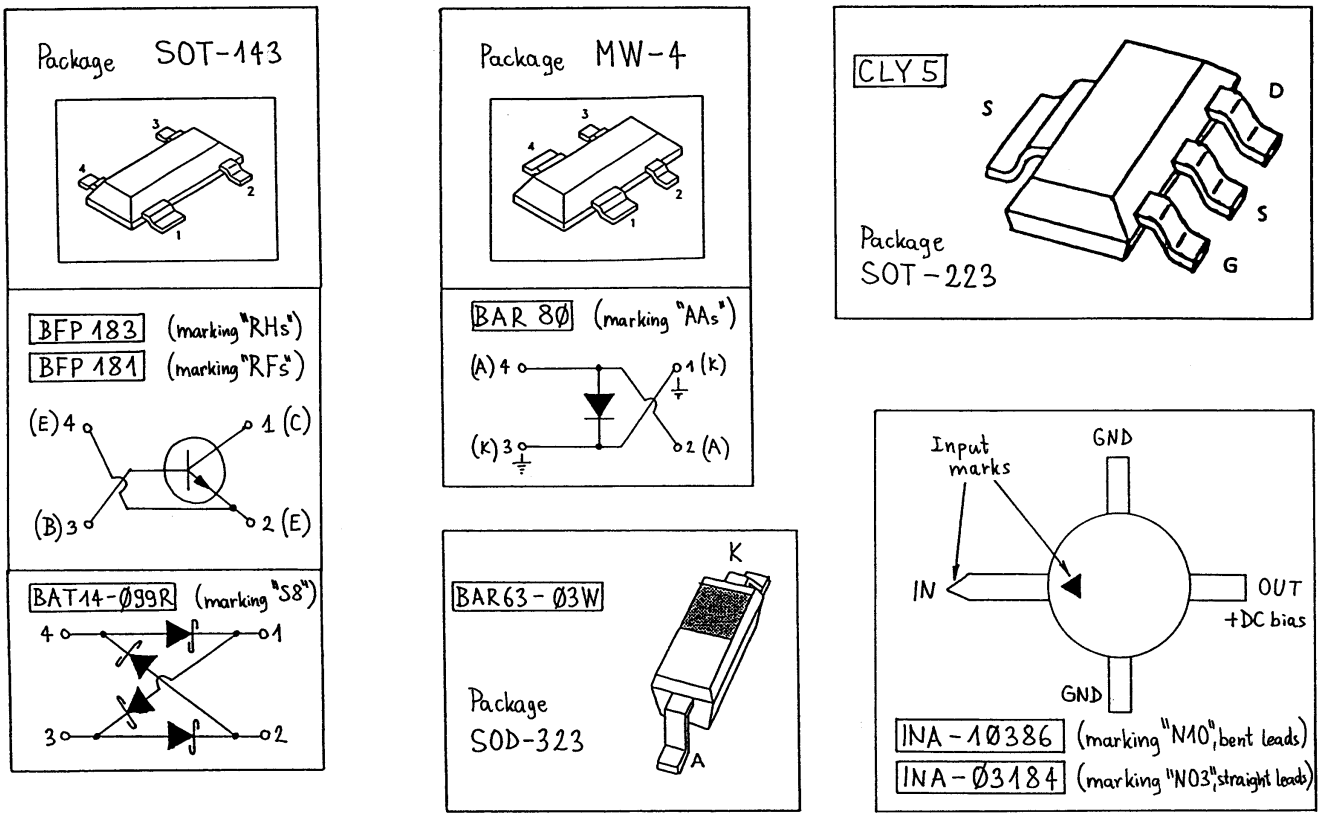


Fig. 26 - SMD semiconductor packages and pinouts.

The assembled PSK transceiver requires little tuning. The only module that needs to be tuned in any case is the local oscillator module. Since most of the stages are just frequency doublers, it is very difficult to tune this module to the wrong harmonic. The TX power amplifier may need some tuning to get the maximum output power. As printed on the circuit board, L1 in the RF power amplifier should not require any tuning if the interconnecting 50-ohm teflon cable from the modulator is exactly 12cm long. Tuning L3 and L6 the output power can only be increased by less than 100mW. All of the other micro-strip resonators should not be tuned. Finally, the 250ohm trimmer in the supply switch interface is adjusted for the maximum TX output power (usually 2/3 of the full scale).

5. Interfacing the 1.2Mbit/s PSK transceiver

Amateur packet-radio interfaces for data-rates above 100kbit/s are not very popular. One of the most popular serial interfaces, the Zilog Z8530 SCC, only includes a DPLL for RX clock recovery that can operate up to about 250kbit/s. Other integrated circuits, like the old Z80SIO, the MC68302 used in the TNC3 or the new MC68360 do not include any clock recovery circuits at all. In addition to the RX clock recovery, data scrambling/descrambling and sometimes even NRZ/NRZI differential encoding/decoding have to be provided by external circuits.

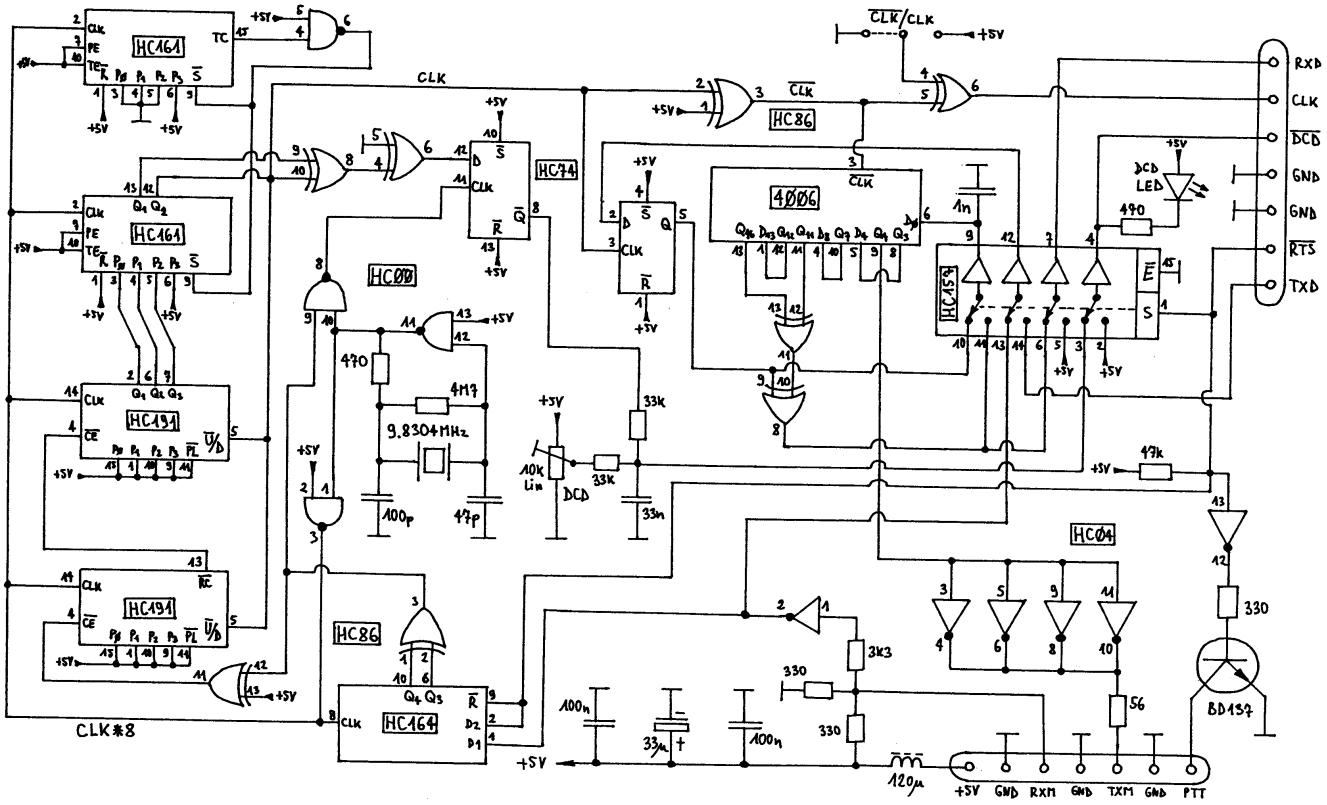


Fig. 27 - Bit-synchronization / scrambler circuit diagram.

The circuit shown on fig.27 was specially designed to interface the described PSK transceiver to a Z8530 SCC, although it will probably work with other serial HDLC controllers as well. The circuit includes an interpolation DPLL that only requires an 8-times higher clock frequency (9.8304MHz), although provides the resolution of a /256 conventional DPLL with a 315MHz clock.

The scrambler/descrambler uses a shift register with a linear feedback with EXOR gates. The scrambling polynomial is the same as the one used in K9NG/G3RUH modems: 1+X**12+X**17. Due to the redundancy in the AX.25 data stream (zero insertion and deletion), a simple polynomial scrambler is completely sufficient to overcome the AC coupling limitation of the described PSK transceivers.

The interface circuit also includes 75-ohm line drivers and receivers, if the PSK transceiver is installed at some distance from the interface. However, connections have to be kept short on the side towards the computer serial port. The described interface only provides one clock signal, since it is intended for simplex operation with the described PSK transceiver. Of course the DPLL is disabled during transmission, so that the circuit supplies a stable clock to the transmitter. The polarity of the clock signal can be selected with a jumper. When

using the Z8530 RTxC or TRxC clock inputs, this jumper should be connected to ground.

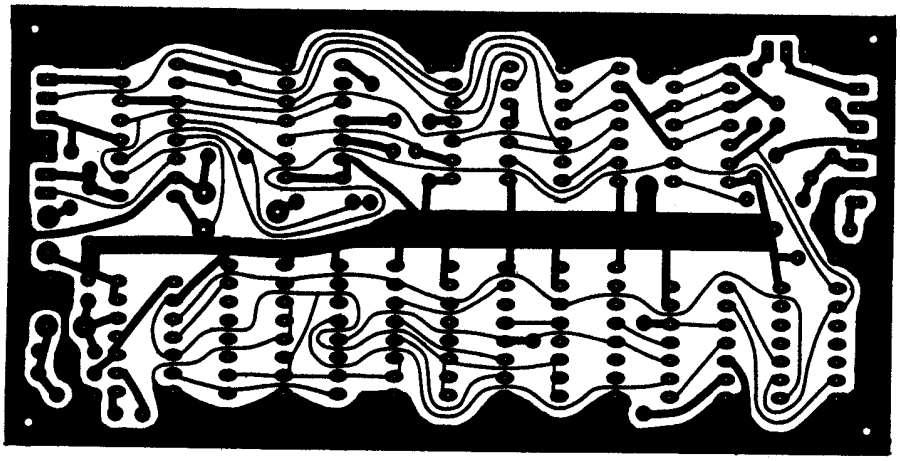


Fig. 28 - Bit-sync / scrambler PCB (1.6 mm single-sided FR4).

The bit-synchronization/scrambler circuit is built on a single-sided PCB as shown on fig.28 and fig.29. It only requires one adjustment, the DCD threshold, and the latter can only be performed when noise is present on the RXM input.

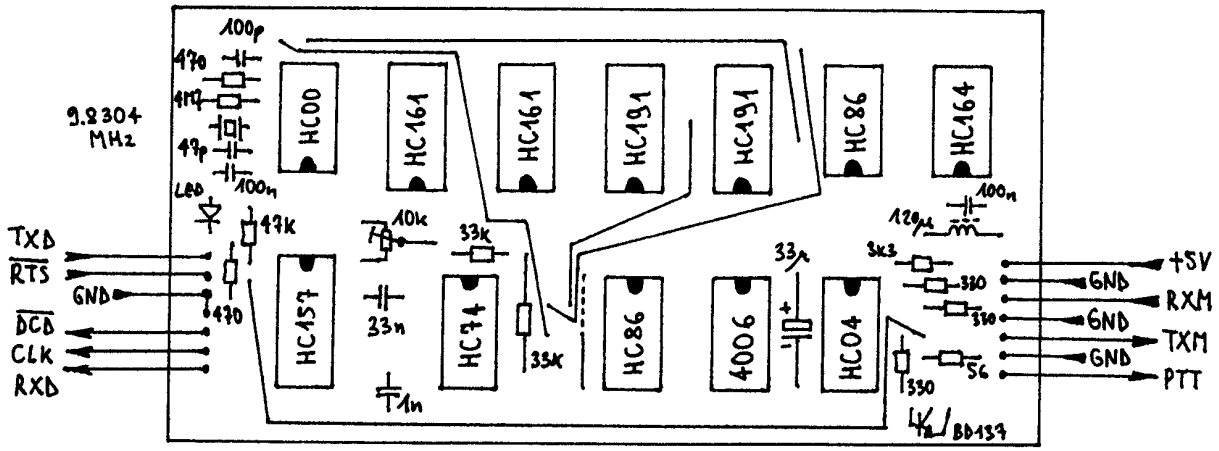
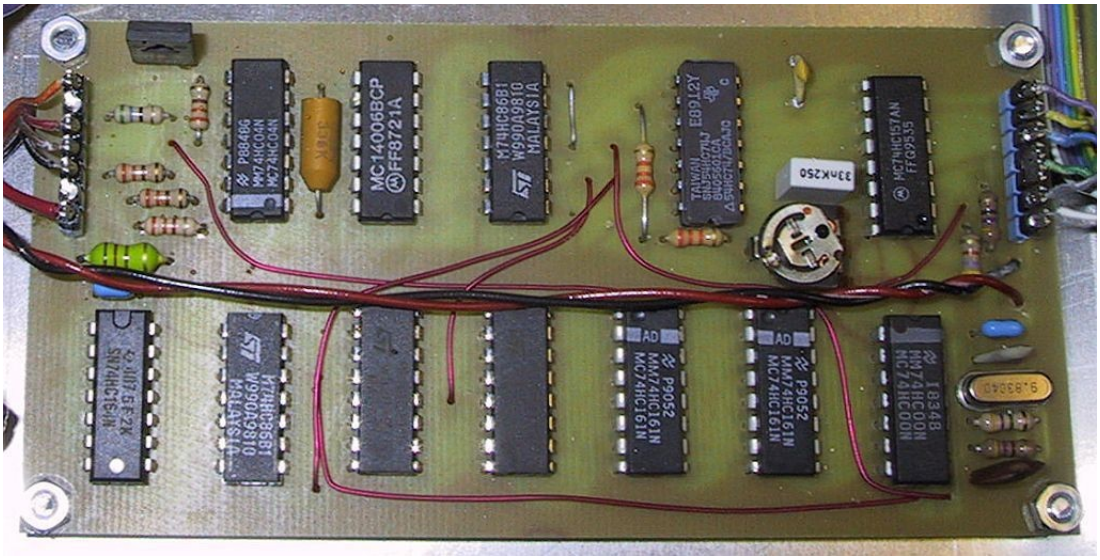


Fig. 29 - Bit-sync / scrambler component location.


MC14006BCP
M74HC86B1
MALAYSIA
33kX250
MM74HC161N
MC74HC161N
MM74HC00N
MC74HC00N

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