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A simple RF/Microwave frequency counter

I decided to design a simple, easily reproducible counter around a PIC 16F876A. The basic counter range is extended to at least 180MHz using two 74Fxx devices. A divide-by-64 prescaler is used for higher frequencies up to at least 4.5GHz. All results of the measurement are shown on an inexpensive, 2x16 alphanumeric LCD module with large characters. A block diagram of the counter is shown in Fig 1.

The counter has three front ends: a microwave (prescaled) input, an RF input and a TTL input. The microwave and RF inputs are AC coupled and terminated at low impedance (around 50Ω). The TTL input is DC coupled and has high input impedance. A progress bar indicator is provided on the LCD display for the gate timing.

Both the microwave and RF inputs have an additional feature, usually not found in frequency counters: a simple signal level detector driving a bar indicator on the LCD display. This is very useful to check for the correct input signal level as well as an indicator for circuit tuning or absorption wave meter dip display.

1. The counter

The whole counter design is based on a 16F876A PIC microcontroller. This includes several peripherals but just a

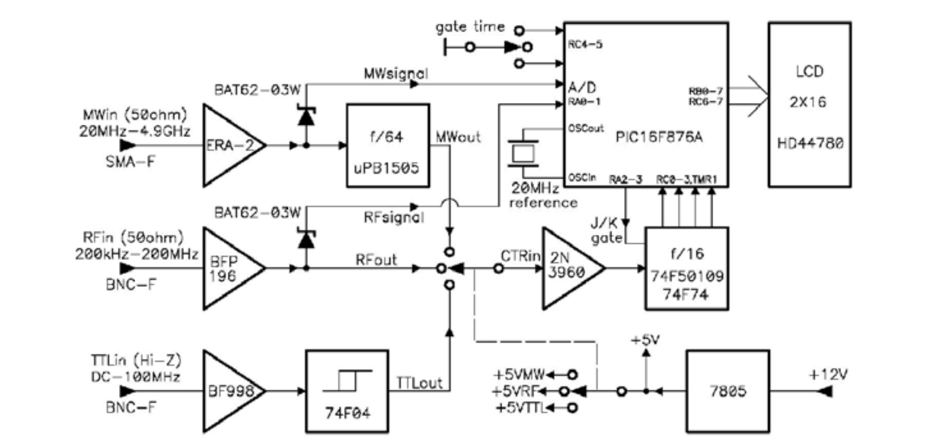

Fig 1: Block diagram of the frequency counter.

few of them are used in this project. The most important in this project are two internal hardware counter/timers called TMR0 and TMR1. The TMR0 timer generates very precise interrupts every 100 microseconds (10kHz) from the 20MHz clock/reference. All required timings for the counter timebase are simply integer multiples of this basic period.

The TMR1 is used as a 16bit (binary) input signal counter. It's maximum counting frequency is just around 16.7MHz. Therefore, the first four flip-flops of the input signal counter chain are added externally as 74Fxxx logic devices. The first two stages use one of the fastest 74Fxxx series devices, the 74F50109 dual J/K flip-flop. The 74F50109 is also specified as metastable immune and is therefore the ideal component for the counter gate. The circuit diagram of the counter is shown in Fig 2.

A more conventional 74F74 dual D flip-flop is used in the third and fourth stages. The TTL flip-flops require pull-up resistors to drive the PIC ports RC0, RC1, RC2 and RC3. RC0 is used as a clock input to the TMR1 at the same time. Replacing the 74F74 with a 74ACT74 could save some current and two pull-up resistors. The 74F50109 has the same pin-out and logical function as the 74F109, but the latter has a lower frequency limit and is not specified metastable free.

The typical frequency limit of the 74F50109 is specified as 150MHz. Driving the 74F50109 with a fast switching transistor 2N3960 (f_t = 1.6GHz) and a schottky diode 1N5712 to prevent saturation, reliable counting can be achieved up to 190 - 200MHz! Unlike conventional AND or OR gates, the J/K gate minimises the jitter of the counting result (wandering of the last digit) regardless of the input signal. Since the /K input of the 74F50109 is inverted, two port pins (RA2 and RA3) of the PIC are required to drive the J and /K inputs with minimal skew.

On the other end, the counter needs to be extended beyond the 4 bits of the 74Fxxx logic and 16 bits of the TMR1 are used adding up to 20 bits of resolution. To avoid disrupting the operation of the main 100µs timer, the TMR1 is not allowed to generate interrupts. The TMR1 overflow (interrupt) flag is checked during every 100µs (TMR0) interrupt. The overflows are counted in two additional 8 bit registers. The overall counter resolution is therefore 36 bits.

These 36 bits are truncated to 32 bits, the upper 4 bits are not used. 32 bits allow counting beyond 400MHz with a resolution of 0.1Hz (gate time 10s). None of these counters is ever reset! The counter value at the beginning of the measurement is stored and subtracted from the end value. Finally, the 32 bit binary result is converted to a 10 digit decimal number and the latter is displayed with the leading zeros blanked, decimal point and units (MHz or kHz).

The basic counter software allows three resolutions (selected with RC4 and RC5): 10Hz, 1Hz and 0.1Hz in direct counting mode (no prescaler), corresponding to gate times of 100ms, 1s and 10s. When used with a divide-by-64 prescaler, the three available resolutions become 1kHz, 100Hz and 10Hz, corresponding to gate times of 64ms, 640ms and 6.4s. All these gate times are obtained by counting the 100µs (10kHz TMR0) interrupts.

The PIC 16F876A drives a standard LCD module with a HD44780 controller and a resolution of two rows of 16 characters each. The HD44780 requires 8 data lines (port B of the 16F876A) and three control signals: Register Select (RC6), Read/Write (GND) and Enable (RC7). Since the data presented on the 8-bit-

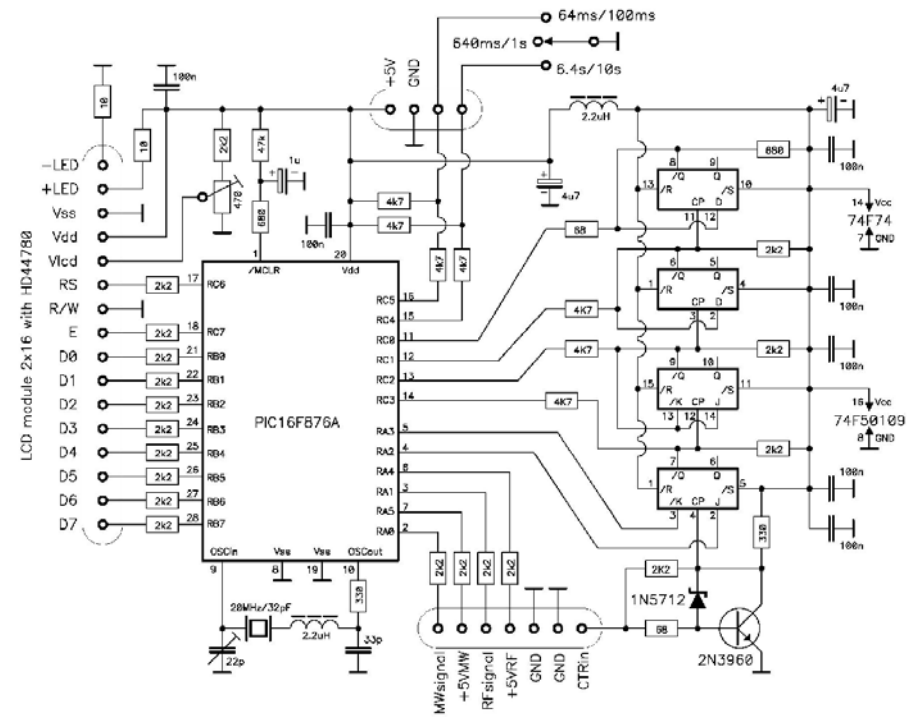

Fig 2: Circuit diagram of the frequency counter.

wide output port RB0-7 is only written to the HD44780, the R/W input is hardwired to ground (/Write). The LCD back light LEDs are supplied through two 10Ω current limiting resistors.

The input signal level is fed to the only

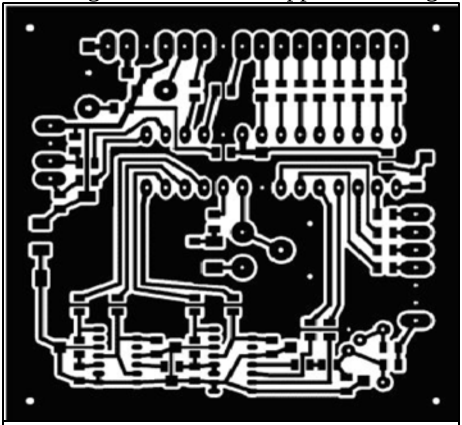

Fig 3: PCB layout for the frequency counter.

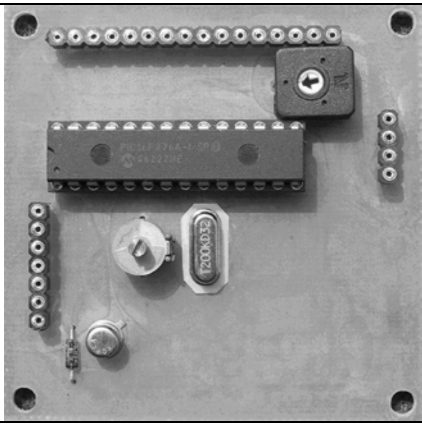

Fig 4: Picture of the component side of the counter PCB.

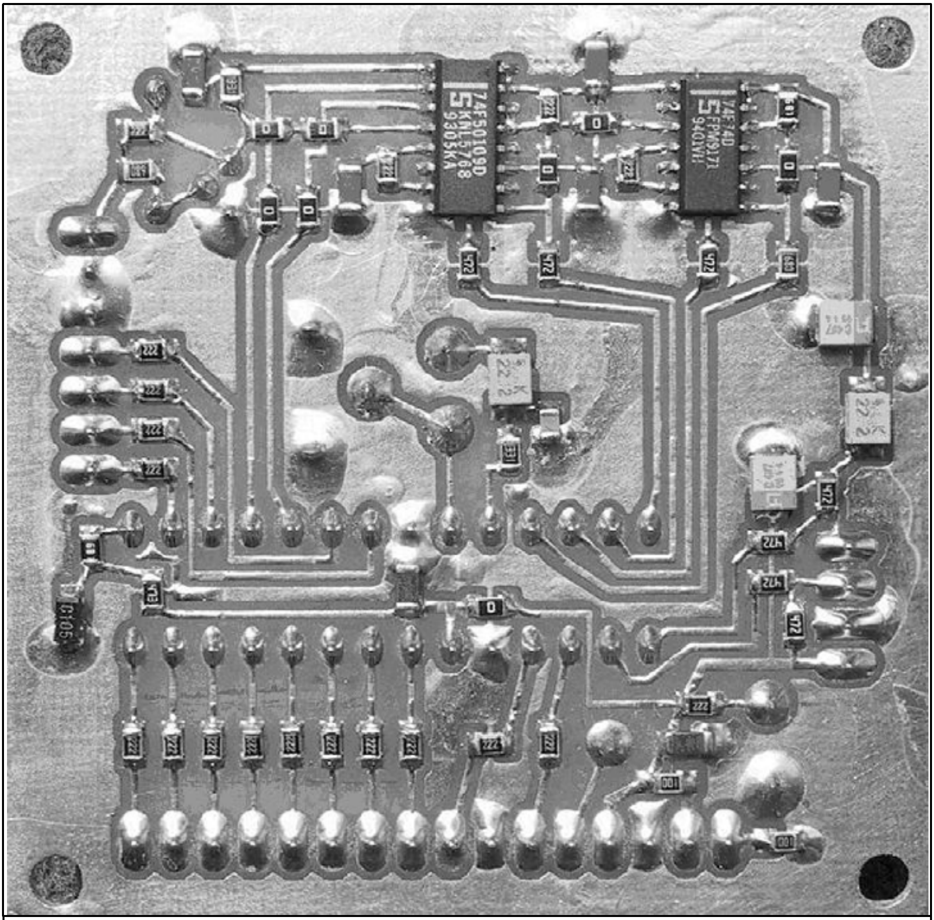

Fig 5: Picture of the track side of the counter PCB with SMD compoenets fitted, note the 0R links.

remaining PIC peripheral used in this project, the A/D converter. The latter has a resolution of 10 bits, but only the most significant 7 bits are used. These drive a bar indicator on the LCD module with 36 segments, corresponding to an input voltage between zero and 1.4V (full scale) on the analogue inputs RA0 (MW mode) or RA1 (RF mode). The operating mode is selected with switches driving the digital inputs RA4 and RA5.

The main counter module is built on a single sided printed circuit board measuring 60mm x 60mm. Good quality IC sockets are used for the PIC 16F876A and as connectors. The PCB layout is shown in Fig 3 and the component layout in Figs 4 and 5.

Most of the components are in SMD packages and are installed on the bottom (solder) side of the printed circuit board. Due to the single sided circuit, many jumpers are required. The PCB is designed for 0805 jumpers shown as 0R on the picture of the completed board Fig 5.

A 20MHz crystal is used both as a clock

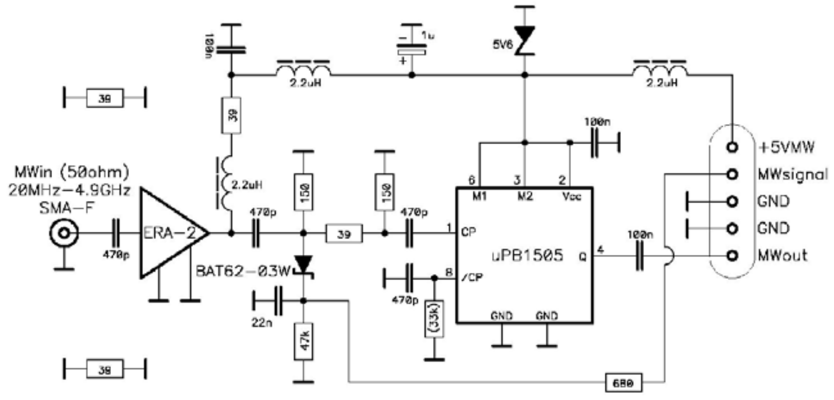

Fig 6: Circuit diagram of the microwave prescaler.

source for the PIC and as a frequency reference for the frequency counter. 20MHz crystals are usually designed either for 20pF - 32pF parallel resonance or series resonance. Since the internal oscillator inside the PIC 16F876A is not able to oscillate on the correct frequency with large capacitors, a series inductor is required to bring the crystal on the exact frequency. The recommended 2.2µH inductor is suitable for 32pF parallel resonance crystals.

Of course, the PIC 16F876A is also able to operate with an external clock source. This has to be connected to pin 9 while pin 10 is left open. If a high quality frequency reference for 5MHz, 10MHz or 100MHz is available, it is recommended to multiply or divide its output to obtain the required 20MHz clock.

Other clock frequencies than 20MHz can be accepted by modifying the software to obtain the 10kHz TMR0 interrupt. The TMR0 time constant allows changing the clock in 80kHz frequency steps (4 clock cycles per instruction and divide-by-2 prescaler for the TMR0). Smaller clock steps of 40kHz can be obtained by inserting NOP instructions in the TMR0 interrupt routine, for example using a high quality (telecom SDH) TCXO for 19.44MHz.

2.

Front ends

The counter is equipped with three different front ends. The front ends are built as separate modules to allow an easy interchange as better components (prescalers) become available or new requirements show up.

2.1 Microwave prescaler

The microwave prescaler front end is designed around the NEC µPB1505 chip, the circuit diagram is shown in Fig 6. This counts up to 4.9GHz and unlike the products from some other manufacturers it is very reliable. An ERA-2 MMIC is used to boost the input sensitivity and provide some protection for the µPB1505. The ERA-2 can accept input signal levels up to +15dBm (30mW). A 6dB attenuator behind the ERA-2 prevents saturating the µPB1505.

A 33kΩ resistor can be used to kill the self oscillation of the µPB1505 around 2.6GHz, but this resistor also adversely affects the sensitivity and the maximum

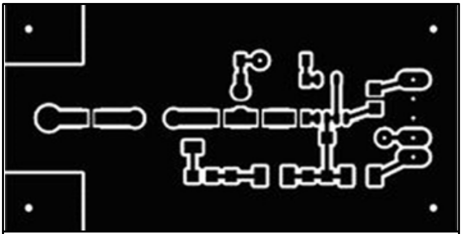

Fig 7: PCB layout for the microwave prescaler.

frequency of the prescaler. A BAT62-03W zero bias schottky diode is used as a signal level detector. The gain of the ERA-2 sets the full scale on the bar indicator to about 0dBm.

The microwave prescaler front end is built on a single sided printed circuit board measuring 30mm x 60mm. The PCB layout is shown in Fig 7 and the component layout in Fig 8. The 50Ω lines are built as coplanar waveguides on a 1.6mm thick FR4 substrate. The input cable is soldered directly to the PCB. To avoid parasitic resonances between the PCB and metal ground plane, two additional 39Ω damping resistors are installed in series with two mounting screws.

2.2 RF front end

The RF front end is designed for a high input sensitivity and low (close to 50Ω) input impedance. The circuit diagram is shown in Fig 9. A high input impedance (as offered in many counters) is actually a disadvantage for RF measurements, last but not least corrupting the measurements due to low frequency (50Hz mains or switching powers supply) interference. The RF front end includes a simple RF amplifier with a BFP196 transistor, an input protection with a 33Ω resistor and a LL4148 diode and a signal level detector using a BAT62-03W zero bias schottky diode.

The RF front end is built on a single sided printed circuit board measuring 20mm x 60mm. The PCB layout is shown in Fig 10 and the component layout in Fig 11

The input cable is soldered directly to the PCB. Since the RF front end does not include any hysteresis, it is not able to operate with sine wave signals at very low frequencies.

2.3 TTL front end

The TTL front end is a high impedance input. DC coupling is necessary to measure pulses with arbitrary duty cycles. The circuit diagram is shown in Fig 12 Further it includes hysteresis for reliable low frequency measurements, regardless of the waveform. The circuit includes a BF998 MOSFET source follower and a 74F04 schmitt trigger. The output of the schmitt trigger is again DC coupled to the 2N3960 in the main counter module.

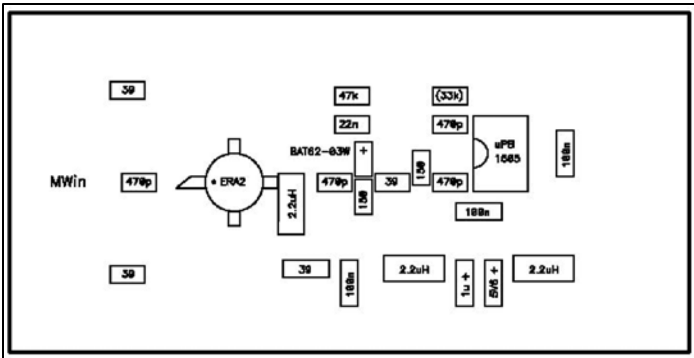

Fig 8: Component layout for the microwave prescaler.

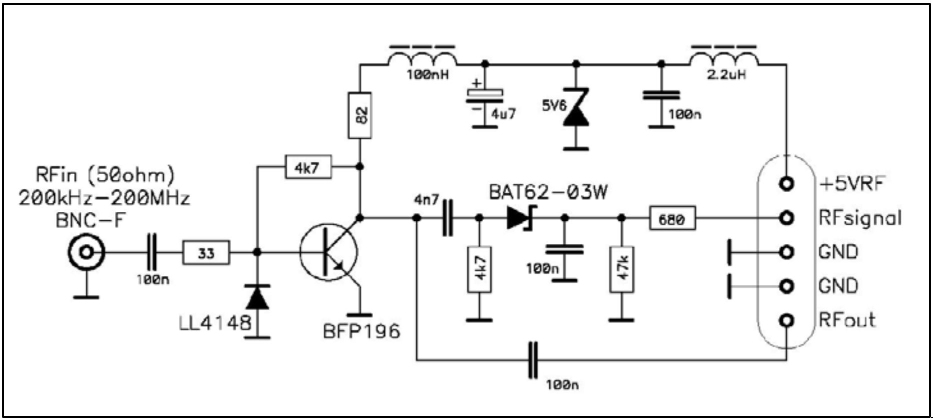

Fig 9: Circuit diagram of the RF front end.

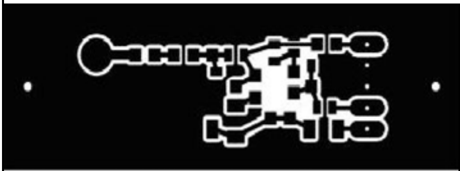

Fig 10: PCB layout for the RF front end.

The TTL front end is built on a single sided printed circuit board measuring 20mm x 60mm. The PCB layout is shown in Fig 13 and the component layout in Fig 14. The input cable is soldered directly to the PCB. Input protection is provided by the 470Ω resistor and the zenner diodes inside the BF998 (breakdown voltage between 8V and 12V). Further protection could be obtained by additional zenner diodes, however the latter may include a large capacitive loading (more than 100pF).

3. Assembly

All counter modules require a +5V power supply. A 7805 regulator is a simple and efficient solution. Some additional components are required for interference and switching transient suppression. The circuit diagram of the power supply is shown in Fig 15 The 7805 regulator is bolted directly to the rear panel for heat sinking.

Two DPDT switches are used for front end selection. An additional switch is used to select the gate time.

All four printed circuit boards are single sided, etched on 1.6mm thick FR4 laminate (image resolution is 150dpi).

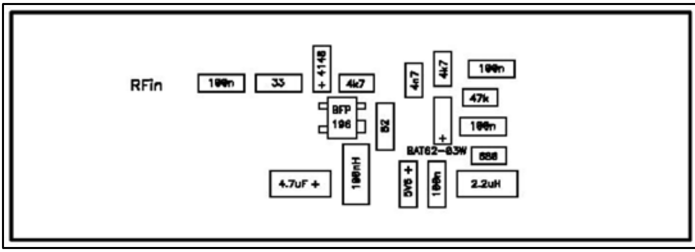

Fig 11: Component layout for the RF front end.

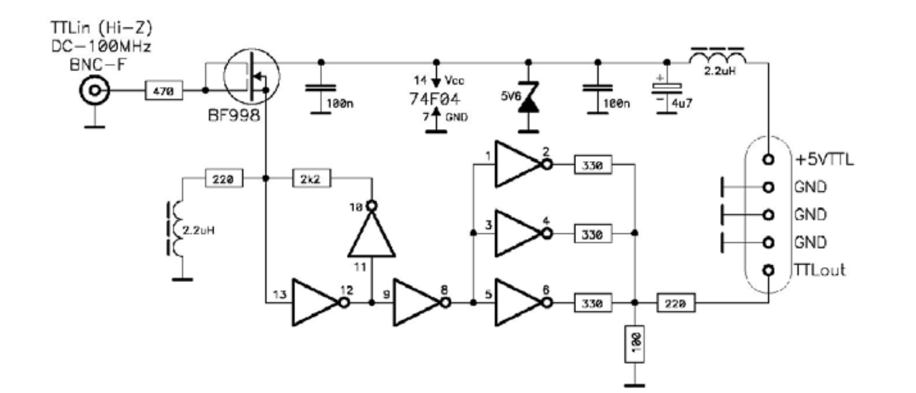

Fig 12: Circuit diagram of the TTL front end.

Fig 13: PCB layout for the TTL front end.

The counter is installed in a box made of aluminium sheet shown in Fig 16. The bottom is made from 1mm thick aluminium sheet, the cover is made from 0.6mm thick aluminium sheet and the LCD is protected by a small piece of plexiglass. The internal width is 200mm, depth 100mm and height 45mm.

The RF connectors, switches and LCD module are installed on the front panel. The power supply connector is installed on the rear panel.

4. Operation

Immediately after power up, the counter displays the software version/date for about one second.

During normal operation, the leftmost characters of both rows are used as a vertical bar display of the gate progress with 10 horizontal segments. The remaining 15 characters in the top row of the display show the measured frequency. Three characters in the bottom row show the operating mode ("MW", "RF" or "TTL") and the remaining 12 characters are used as a horizontal bar display of the signal strength with 36 vertical segments.

In the microwave mode both prototypes

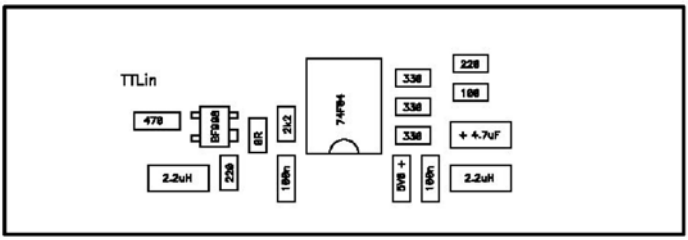

Fig 14: Component layout for the TTL front end.

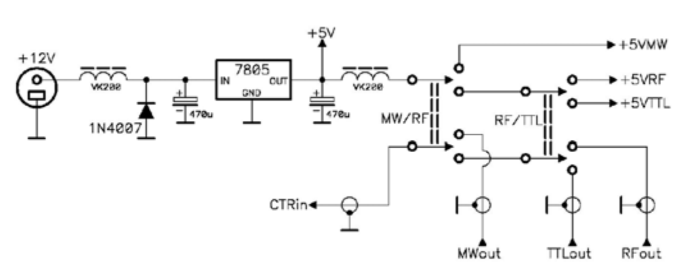

Fig 15: PSU circuit diagram for the frequency counter.

operated reliably up to 4.9GHz with an input signal level of 0dBm (self oscillating μPB1505 without 33kΩ resistor). Below 3GHz the sensitivity improves to -30dBm. The 33kΩ unbalancing resistor to stop self oscillations degrades this sensitivity by more than 10dB! Below 500MHz the sensitivity degrades again: the counter may count odd harmonics with too low signal levels. The minimum usable frequency was found around 12MHz. Fig 17 shows the counter in the microwave mode with a gate time of 640ms corresponding to a resolution of 100Hz.

In the RF mode the 74F50109 allows counting up to about 220MHz. Reliable operation is possible up to 190-200MHz, depending on the internal wiring to the switches, with an input-signal level of 0dBm. The sensitivity improves from -20dBm at 180MHz down to -50dBm at 10MHz. The RF signal-level meter follows a similar increase in its sensitivity. This increase at lower frequencies matches the performance of the described loop probes!

Unfortunately, the 74F50109, manufactured by Signetics (Philips) is not easily available. A 74F109 from the same manufacturer only operated up to about 140MHz. A combination of 74AC109 and 74AC74 (both from National Semiconductor) counted up to about 170MHz. The 74ACxxx logic circuits require a different input DC bias: replace the 2.2kΩ resistor between the input and the collector of the 2N3960 with a 47kΩ resistor. All four pull-up resistors can be omitted with 74ACxxx logic. Finally, the 2N3960 itself does not have many valid replacements. A 2N2369 will decrease the 74F50109 counting rate down to just 165MHz while RF and microwave transistors provide

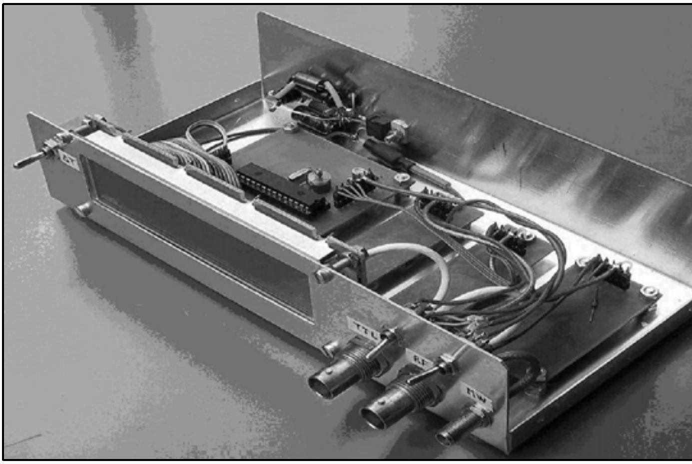

Fig 16: A picture of the completed frequency counter.

Fig 17: The counter in the microwave mode with a gate time of 640ms corresponding to a resolution of 100Hz.

even worse results!

In the TTL mode the prototypes operated reliably beyond 100MHz. This frequency limit is however reduced by the coaxial cable feeding TTL signals and even more when using oscilloscope probes. The input signal level is not indicated in the TTL mode. The built in hysteresis allows reliable counting of very low frequencies, like the 50Hz mains.

The current software version does not detect the mode switching before the end of the gate period. Therefore one may have to wait up to 10 seconds for the gate period to expire and another 10 seconds to get some meaningful reading. The current software also does not make any use of the measured signal level. Therefore it will display the self oscillating frequency of the prescaler with no signal input in the microwave mode or any other invalid data due to low signal levels in the RF or microwave modes.
The software is designed using the same rules as the whole counter: keep this project useful, simple and straightforward. A simple prescaler is therefore used in place of a considerably more complex direct microwave counter. Some simple 74Fxxx logic ensures enough overlap between the prescaled microwave frequency range and the direct RF frequency range. A TTL input with hysteresis is an efficient solution for low frequencies and extreme duty cycles. Finally, an input signal level indicator is an inexpensive but very useful addition to a frequency counter.

Last but not least, all detailed information like PCB files or software source code are available on Matjaz Vidmar's web site [2].

5. Probes

A very common problem of many frequency counters is that these are supplied to the end user without (any) suitable probes! In fact, most RF/microwave sources cannot be connected directly to a counter input. The conventional oscilloscope probe is not a good solution for most RF/microwave measurements either. Worst of all, most counters are not even designed to be used with some useful probe types.

Any serious RF/microwave engineer has his/her own set of suitable attenuators, circulators, loads and directional couplers to connect spectrum analysers, power meters, counters and other instruments to the circuit under test. A complete set of transitions between different RF connectors is also required. Finally, a number of pigtailed connectors to be soldered directly to the circuit under test is always of great help.

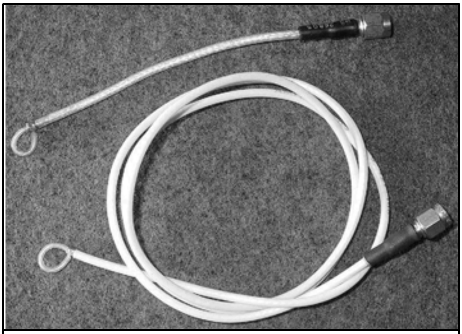

Fig 18: Loop probes.

A very useful probe to be used with RF/microwave counters is a simple inductive pickup or in other words a 5mm diameter loop at the end of a short length of 50Ω coaxial cable. According to my own experience it does not make sense to make this loop much smaller or larger than 5mm. The same loop can be used from a few MHz up to several GHz. A small resistor (around 50Ω) can be installed in series with the loop to suppress any cable resonances.

The loop is simply approached to inductors or resonators in the circuit under test (Fig 18). The undesired loading of the circuit can be minimised by keeping the loop at the maximum distance that still provides a stable reading on the counter. Finally, the loop probe is never affected by low frequency (50Hz mains or similar) interference. Since the coupling to the circuit under test is not very efficient, it is rather unlikely to damage the counter with large RF signal levels.

A standard oscilloscope probe is a practical solution to measure low frequencies, pulsed signals and in some cases even RF signals. In order to use an oscilloscope probe efficiently, the internal operation of the probe has to be understood (Fig 19). Most probes are equipped with a X1/X10 switch. Further there is a series damping resistor (around 500Ω) to avoid cable resonances that could both corrupt the oscilloscope display and severely disturb the circuit under test. Finally, one should understand that although the TTL input of the counter operates in excess of 100MHz, the oscilloscope probe may reduce the upper frequency limit to 50MHz or even less!

6. References

[1] 13GHz prescaler, Zeljko Bozic, VHF Communications Magazine, 2/2006, pp 89 – 94

[2] Matjaz Vidmar web site for frequency counter http://lea.hamradio.si/~s53mv/counter/history.html

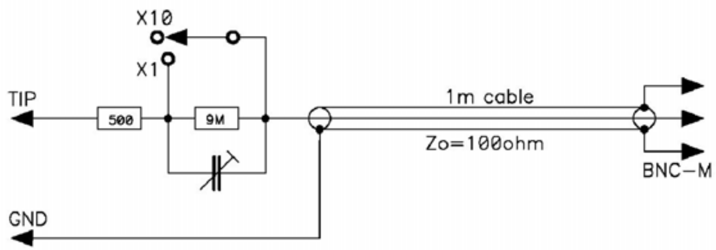

Fig 19: Circuit diagram of a standard oscilloscope probe.