Dragoslav Dobričič, YU 1 AW

Low-Noise 144 MHz Pre-Amplifier Using Helical Tuned Circuits

The introduction of field effect transistors (FETS), especially those made from gallium-arsenide (GaAs), in low-noise pre-amplifiers was a significant step forward in a field hitherto dominated by parametric and MASER amplifiers. With the advent of EME and satellite communications, amateurs are beginning to improve their receiving systems with pre-amplifiers. Before, however, low-noise transistors are employed for this purpose, there are one or two things which have to be taken into account.

It is widely believed that it is sufficient just to bring a GaAs-FET into operation in order to obtain the noise figure published in the databook for the device. The reality is, however, a little different owing to the losses in the input tuned circuits. These losses have the effect of directly increasing the noise figure of the amplifier. Even using an excellent transistor, the pre-amplifier can be rendered worse than useless if due attention is not paid to the input circuit losses.

1. A LITTLE THEORY

A transistor, intended for low-noise pre-amplifiers, can only achieve the specified noise figure if certain working conditions are exactly adhered to. First of all, the important parameters, drain-source voltage (U_{DS}), gate-2 source voltage, (U_{G2S}) and drain current (I_D) should all be precisely defined. How important, above all, the drain current is can be seen in **fig. 1**.

A further important condition is that the transistor input "sees" a definate impedance Z_{NF} at which its noise is at a minimum. With most FETs, and especially with GaAs-FETs, this impedance Z_{NF} differs widely from that at which the transistor

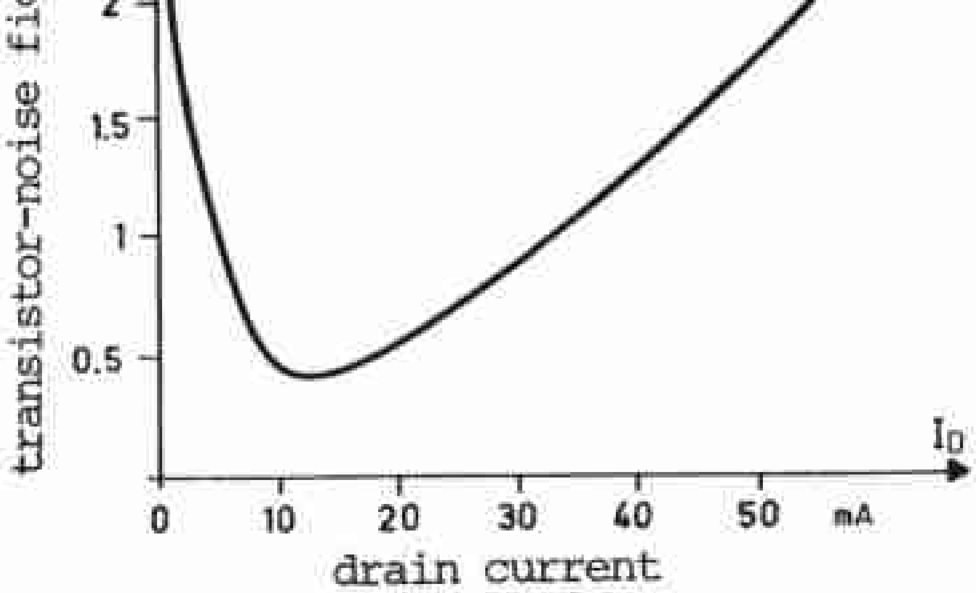

Fig. 1: FET noise figure as function of drain current I_D

transistor type	loss min. (dB)	L 1 turn	C_c pF	C_i pF	U_b V	U_{DS} V	U_{G2S} V	I_D mA	R_s Ω	R 1 Ω	R 2 Ω	R_D Ω
BF 981	0.1	4	4.7	2	12	10	4	10	10 - 50	10 k	15 k	150
MGF 1200 MGF 1400	0.15	5	2.7	3	5	3	–	10	* 100	–	–	100
CFY 13 CFY 14	0.15	5	2.7	3	5	4	–	10	* 100	–	–	10
CF 300	0.36	5	1.6	2	6	5	2	10	* 100	10 k	15 k	10

Table 1: Element values for pre-amplifiers

* approximate value (see text)

delivers a maximum power transfer. That is, the noise matching reduces the transistor's amplification but the lower noise figure is by far the highest consideration. A high amplification, indeed, can be positively disadvantageous (1).

The setting of the correct transistor working potentials and currents is normally no real problem, but a few things have to be observed. The problem of arranging the gate to look into an impedance Z_{NF} is more difficult because of the

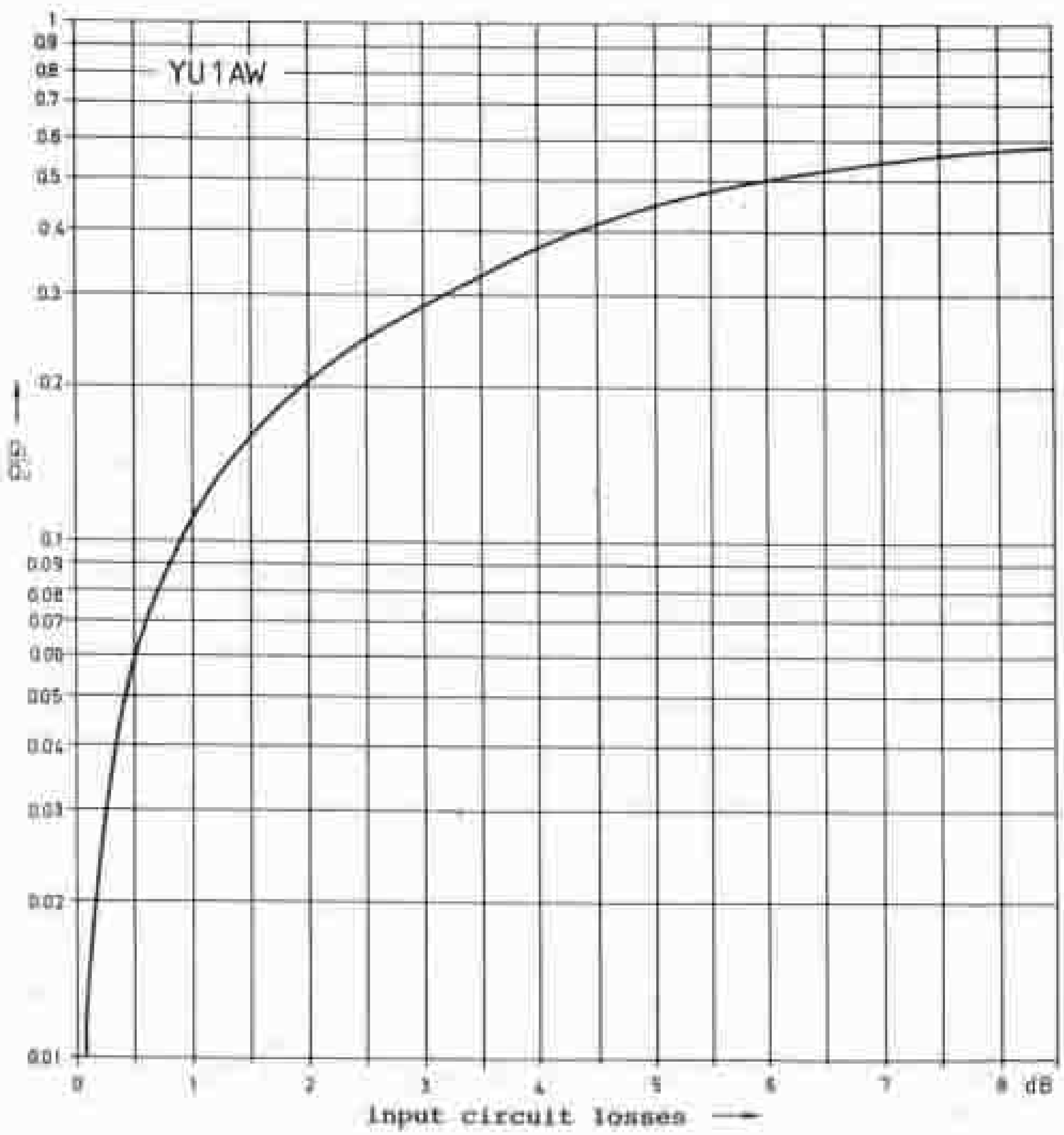

Fig. 2: Circuit losses (dB) as function of Q_l / Q_u ratio

transistor	MGF 1200				BF 981					CF 300		
input circuit	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Q_u	307	709	225	113	307	709	225	213	165	307	709	154
Q_l	11.2	11.2	17.1	17.1	4.5	4.5	4.5	4.5	6.3	29	29	29
min. loss (dB)	0.24	**0.14**	0.69	**1.43**	0.13	**0.06**	0.18	0.19	0.34	0.86	0.36	**1.8**

Table 2: Comparative data for different published pre-amplifiers

losses entailed in transforming from the antenna impedance (normally 50 Ω) to Z_{NF}.

The losses L of a matching circuit are determined by the relationship of the loaded Q (Q_l) and the unloaded Q (Q_u).

$$L = 10 \log \left(\frac{1}{1 - Q_l / Q_u} \right)^2$$

It may be seen from this formula that the losses are smallest when Q_l / Q_u is as small as possible, i.e. Q_l must be as small as possible and Q_u must be as high as possible (**fig. 2**)

Q_l and Q_u are determined from physical and technical characteristics. By the correct choice of circuit parameters and a careful construction, the optimum value for Q_l and Q_u can be achieved and thereby the losses for a particular application minimised.

Q_l should then be as small as possible. The lower limit is determined by the transformation ratio $n = Z_{ant}/Z_{NF}$. The minimal value for Q_l can then be expressed as: –

$$Q_l\,(\min) = \sqrt{n - 1}$$

Sometimes the value required for Z_{NF} entails a value for Q_l which is above the minimal value according to the above formula. This value of Q is determined by the ratio of imaginary to real parts of the impedance Z_{NF}: –

$$Q_d = X_{NF}/R_{NF}$$

The important consideration when designing pre-amplifier input circuits is that the value for Q_l is determined by that required for correct noise impedance match and will be generally higher than Q_d or Q_l (min). The increasing of Q_l owing to Q_d would explain why many transistors work better in certain frequency bands than in others. The correct choice of transistor is determined then, upon the Q_d at the working frequency. For example, on account of the large relationship of Q_d at low frequencies (below 1 or 2 GHz), the majority of the well-known GaAsFETs are ineffective in the 2 metre band. A larger value of Q_d, and with it Q_l, increases the input circuit losses such that the minimal value for noise-figure cannot be attained. The result can be worse in practice than using much cheaper transistors (**table 2**).

Q_u depends upon the circuit itself, its arrangement, the number, type and manner of operation of the components used. Q_u is higher if the individual components employed also have a high Q, that is, they are of high quality and the component-count is kept to a minimum.

Intrinsic losses and radiation losses are two factors which must be kept under control. In most proprietry pre-amplifiers, the inductors are mounted upon a printed circuit board and usually have significant radiation losses. Good insulation materials are a must. Air is, without doubt, number one, PTFE (teflon) and high-frequency ceramic can also be recommended.

The resistance of conducting materials must be held to as low a level as possible in order to minimise losses by skin-effect. For this reason, higher-conductive metals, such as copper and silver, are used and also metals of a non-oxidising nature (gold, platinum). These measures help to achieve high-Q values in circuit elements.

At lower frequencies, the inductor losses are the chief cause of the problem as they, in practice, determine the Q_u of the resonant circuit. At higher frequencies, the losses are considerably reduced by the use of strip-lines and coaxial resonators which mean higher values for Q_u.

Also the relationship between inductance and capacitance (L-C ratio) influences the value of Q_u. Using a higher value of inductance and a lower value of capacitance for a given resonant frequency, means that the unloaded Q (Q_u) is higher.

The minimum number of elements, required to undertake an impedance transformation, is two. The circuit is known as an "L section" network and consists of a capacitor and an inductor. This circuit has the disadvantage that the loaded Q (Q_l) cannot be independently variable but is fixed for a given transformation ratio.

Three elements in a transformer circuit, allow n and Q_l to be selectable independently from one another and within certain limits, may be varied thus making the tuning easier. From the many possible circuits using three elements, the Pi and the parallel tuned circuits are the ones most frequently used.

Additional losses can occur owing to the chokes and resistances used for the working point setting of the pre-amplifier. This applies also to the capacitors for coupling and decoupling. For this reason it is best to incorporate tuned and transformation circuits into the active devices' electrode supply leads.

Bearing these points in mind, the input circuit of **fig. 3**, using a capacitive coupling to the antenna, may be regarded as satisfactorily fulfilling these requirements. Using striplines or coaxial lines, instead of coils, results in an increased Q_u but at 144 MHz, the line would be more than 30 cm long and therefore unpractical. Normal coiled inductors have a Q which is directly proportional to the coil diameter and the square root of the frequency for a given inductance. This means having fewer turns but an unwieldly large diameter to achieve the necessary Q_u.

The solution is the helical circuit, a kind of coaxial resonator with a spiral-formed inner conductor (2, 3). This arrangement results in a decreased propagation factor for the circuit, and thereby the length of the λ/4 or λ/2 line element, quite considerably. At the same time, all the advantages concerning low losses are retained thereby endowing the helical tuned circuit with a Q which is many factors higher than a coil tuned circuit of similar dimensions. Also, as shown in fig. 2, the losses are considerably lower with a reduction in the relationship Q_l/Q_u.

Helical circuits are employed in proprietary receivers but either in an actual or a conceptually incorrect manner. Conceptually: the input circuit was designed for a high selectivity before the first transistor was mostly using a three-stage helical filter with loose coupling to obtain a high Q_l and a narrow bandwidth. Because Q_l was nearly as high as Q_u, the filter exhibits a high loss (8 to 12 dB) and the resulting noise figure was miserable, as a series of tests have confirmed. These filters were therefore removed in order to

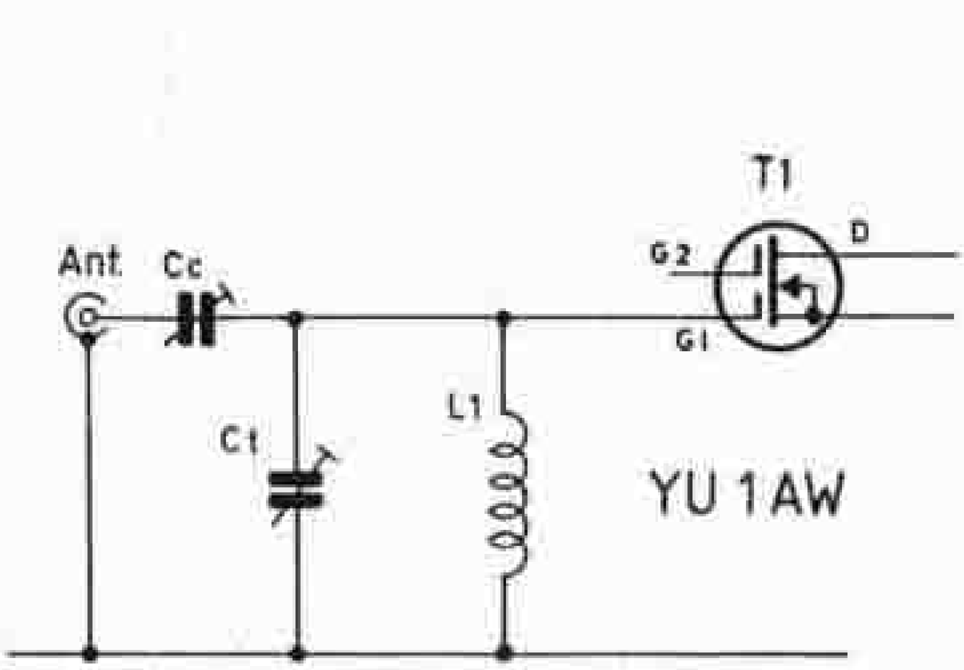

Fig. 3: Parallel input circuit with capacitive loading control

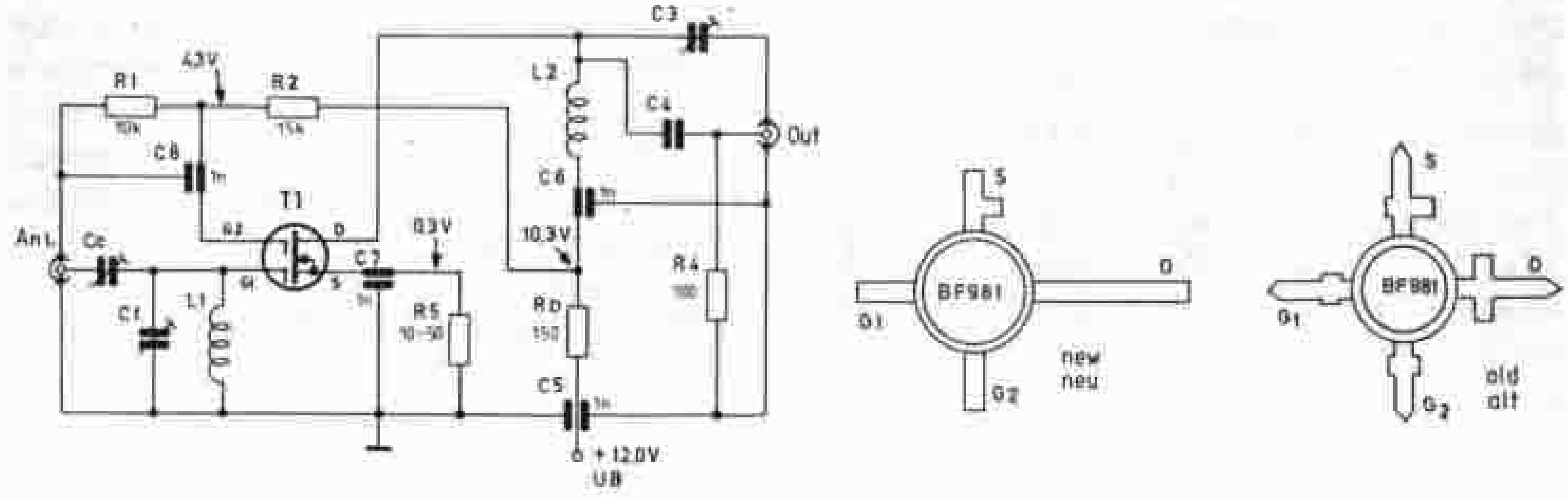

Fig. 4: Circuit schematic of pre-amplifier using BF 981

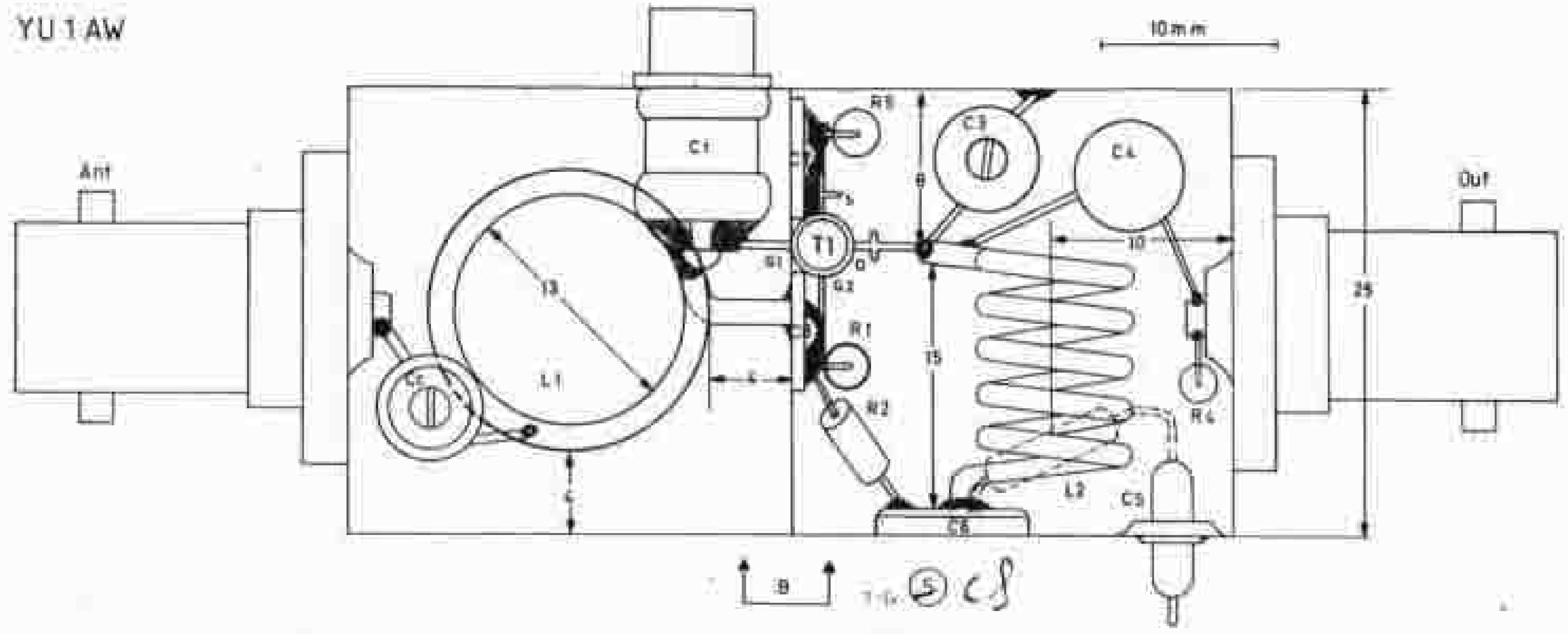

Fig. 5: Plan-view [A-A] of pre-amplifier constructed from fig. 4

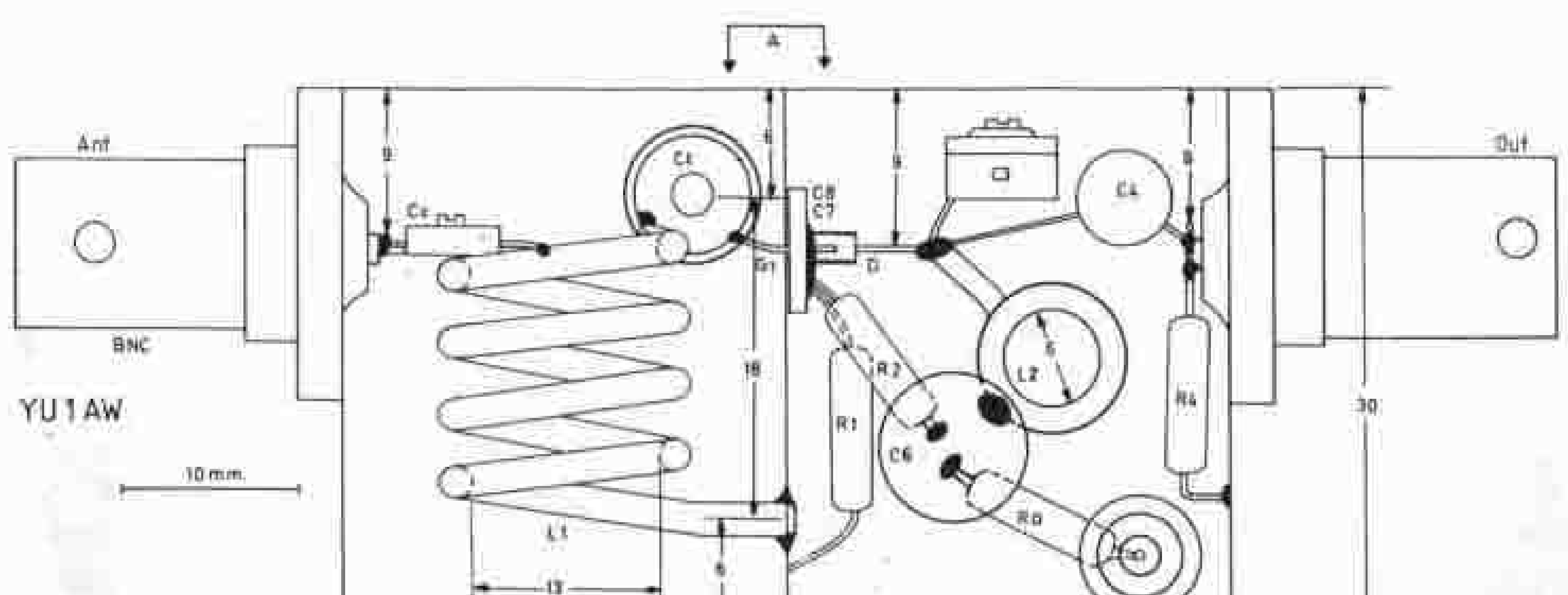

Fig. 6: Side-view [B-B] of pre-amplifier

bring the noise figure down to an acceptable value of 3 dB – normal for the transistors used.

In the pre-amplifier to be described, the helical circuits are employed in quite a different fashion. The ratio Q_l/Q_u is made small by using a large value for Q_u and thereby sharply reducing the losses. In other words, the replacing of a coil by a helical tuned circuit and arranging for the Q_l to be the same, the ratio of Q_l/Q_u is more favourable. The improvement thereby obtained is considerable and can be seen in the results of **table 2**.

The construction and adjustment of helical circuits are really simple and, if care is taken over the relationship of the geometric dimensions, not at all complicated. This is important because the desired results are only achieved when the construction is easily reproduceable.

The author designed the pre-amplifier for his EME-station. The GaAs-FETs MGF 1200 and CFY 13, as well as the MOSFET BF 981, are employed in circuits which were computed with the aid of a computer program "YU 1 AW MATCHNET". All these circuits were superior to previously published designs and confirmed the theoretical considerations outlined in this article. The input circuit losses were reduced by about 0.1 dB.

The author has now checked over 25 published designs with this program and obtained some pretty shattering results. The input circuit losses lay between 0.2 and 1.6 dB, which doe not include additional losses caused by radiation, poor feed-in or incorrect coil-tapping, unsuitable layout, drain-current too low, etc. Some of the examples can be found in table 2. Many of the pre-amplifiers tested claimed noise figures which lay under the figure for the input circuit losses! This shows that many designers neglect the negative influences of the input circuit and give the noise figure of the pre-amplifier as that published for the specified noise-figure for the transistor in its data sheet.

2. MOSFET PRE-AMPLIFIER

All these findings were applied to the construction of a pre-amplifier which would be capable of outperforming all existing designs inasmuch that all the conditions outlined earlier would be fulfilled. Only by using helical tuned circuits, it is possible to construct a 2 m-band pre-amplifier with a noise figure which only exceeds that of the transistor used by 0.1 dB. The construction using the MOSFET BF 981 (**fig. 4**) yields an unloaded Q (Q_u) of about 700 and a loaded Q (Q_l) of 4.5. The input loss is then computed to be 0.1 dB.

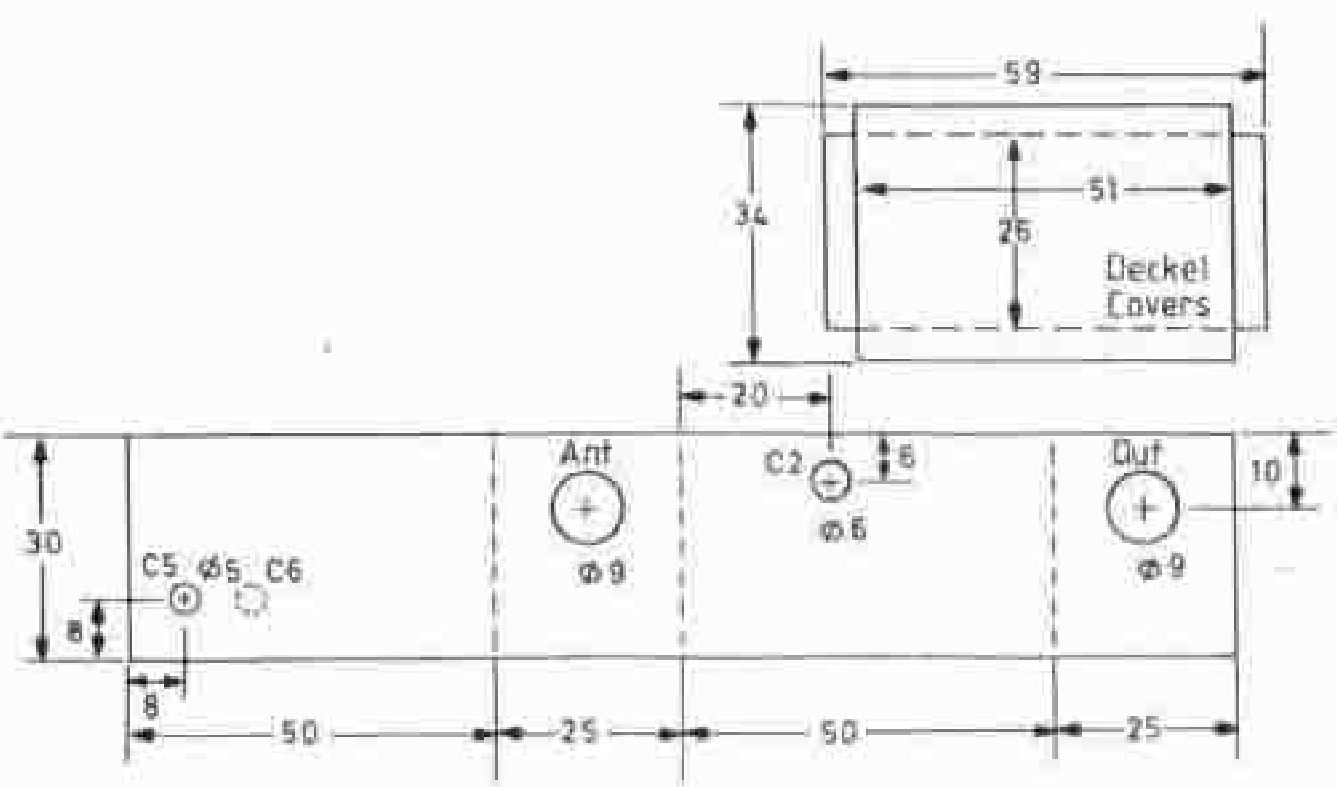

Fig. 7: Material working dimensions for pre-amp. box

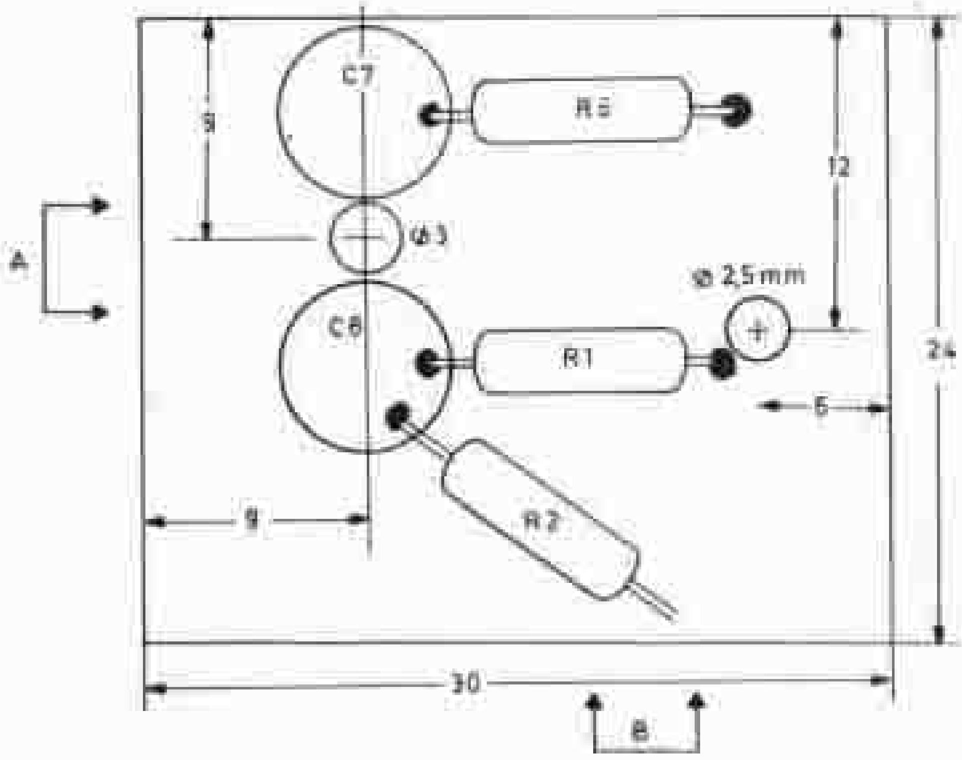

Fig. 8: Details of screen-mounted components

Figures 5 and 6 show the arrangement with the necessary dimensions given for two planes. The input and output socket utilise BNC flange receptacles soldered directly to the metal face. In the helical resonator enclosure, the tuning capacitor C_t and the antenna coupling capacitor C_c are to be found. The other compartment contains the drain tuned circuit suitably damped by resistance R4 (1) in order to reduce the amplification and at the same time to improve the matching to the following receiver. The coils are mounted perpendicularly with respect to each other in order to reduce the possibility of unwanted coupling to a minimum.

The pre-amplifier is housed in a container made from 0.5 mm thick brass or copper (**fig. 7**) and the input circuits separated from the output circuits by a metal separating screen. This dividing wall has a 3 mm hole, drilled in it through which the gate 1 lead is passed. As shown in **fig.8**, on each side of this hole are soldered chip capacitors. These are connected to the source and gate 2 and also the resistors which set the working point. The supply voltage is introduced by means of a soldered-in feed-through capacitor.

The housing is sealed with soldered-on lids, both above and below the helical tuned circuit so that the amplifier can function in stable conditions and not to be subjected to interference fields. The layout is such that fitting and subsequent removal of the two covers should not adversely affect the amplifier performance. The adjustment of this pre-amplifier is quite simple.

First of all, the drain current is determined by measuring the PD across the drain resistance R5. If the drain current is smaller than 10 mA or greater than 15 mA, the resistance R5 must be changed accordingly.

Following this adjustment, the pre-amplifier is connected between antenna and receiver and the trimmer C_c adjusted to that indicated in **table 1**. Alternatively, a suitable fixed capacitor may be also soldered in and the other trimmers tuned for maximum amplification using a low-level signal source.

If a noise generator, noise comparator (4) or noise test-set (5) is available then the optimum adjustment for C_c and C_t can be quickly found. Otherwise an approximation's method must be employed. This consists of increasing the value of trimmer C_t off the point of maximum gain until the output has dropped some 2 to 3 dB. This is approximately the tuning for minimum noise figure, verified by the author on a number of examples.

It should also be mentioned that it is very important to employ only the best-quality trimmers with air as the dielectric or perhaps ceramic or PTFE.

Owing to the low-loaded Q of the tuned circuit, the bandwidth of the amplifier is relatively high so that no retuning is necessary across the whole of the two-metre band.

With R4 shunted across the output, the gain is reduced to some 16 dB. If a gain adjustment is required this resistor may be raised to increase the gain or C4 lowered.

The only element whose value cannot be definately given is the source resistance R_s. This lies between 10 and 50 Ω according to the value of the transistor's I_{DSS}. This production spread in tolerances is quite normal for FETs.

Noise-figure measurements carried out on several selected BF 981 (about 0.8 dB) showed that the pre-amplifier noise figure lay only 0.1 dB above that for the transistor alone. This verified the theory and justified the whole effort. All the expectations were fully achieved and therefore no improvements or modifications were necessary. A few of these amplifiers were used for EME and MS work and others are in constant use with some keen tropo-DX-ers.

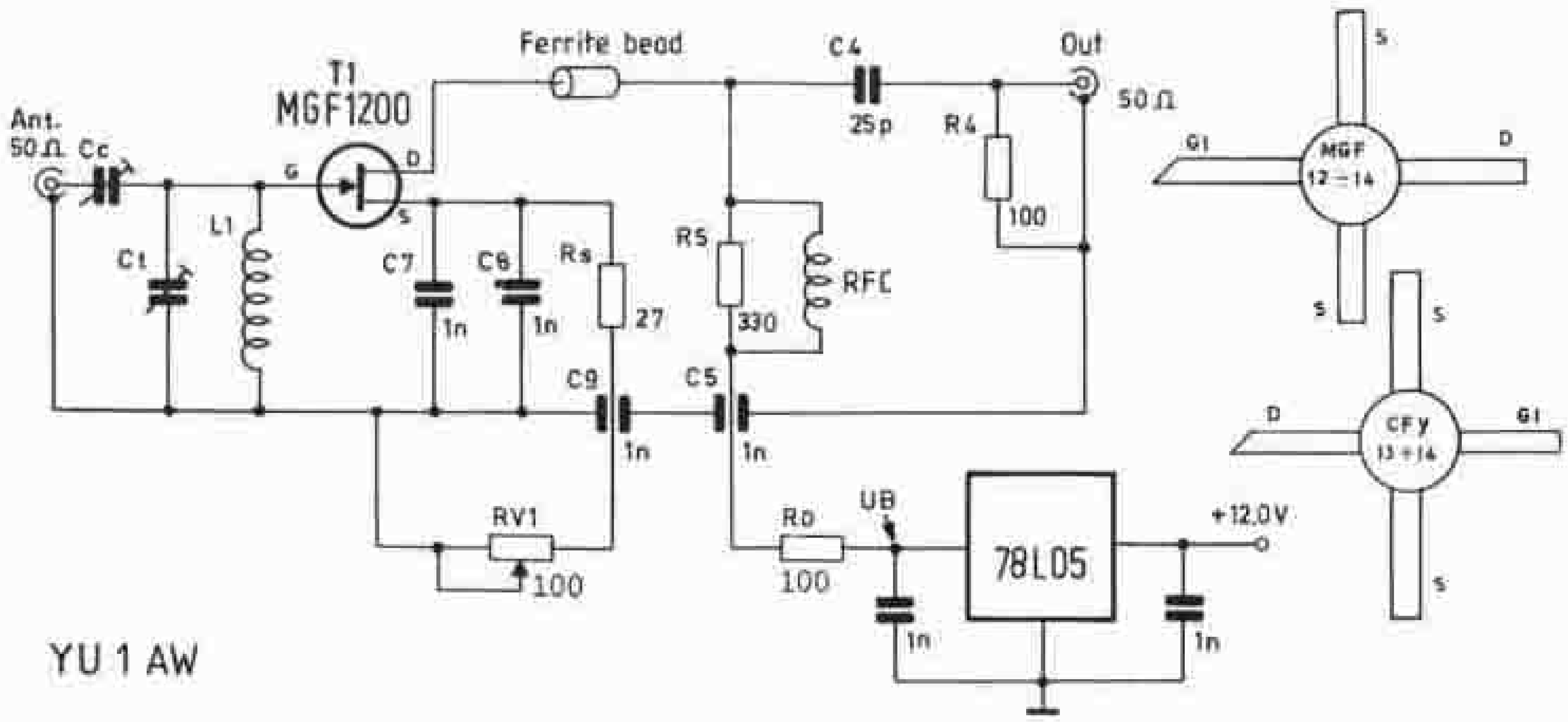

Fig. 9: Circuit schematic of pre-amplifier using GaAsFETs

3. A PRE-AMPLIFIER USING GaAs-FETs

Several other pre-amplifiers were equipped with one or two-gate GaAs-FETs, the MGF and CFY series and also the CF 300. The latter was very hard to match in the two-metre band but was much better in the 70 cm and 23 cm bands in this respect and was very much easier to work with.

The circuit diagram of an MGF 1200 pre-amplifier may be seen in **fig. 9**. The input is identical with that in fig. 4 except that L1 here is only five turns. The output circuit is non-resonant.

All GaAs-FETs are very difficult to match at low frequencies and are only conditionally stable at frequencies under 2 GHz. Conditionally stable means that they can, under certain circumstances, start to self-oscillate especially under conditions where maximum gain is being extracted. Conditionally stable pre-

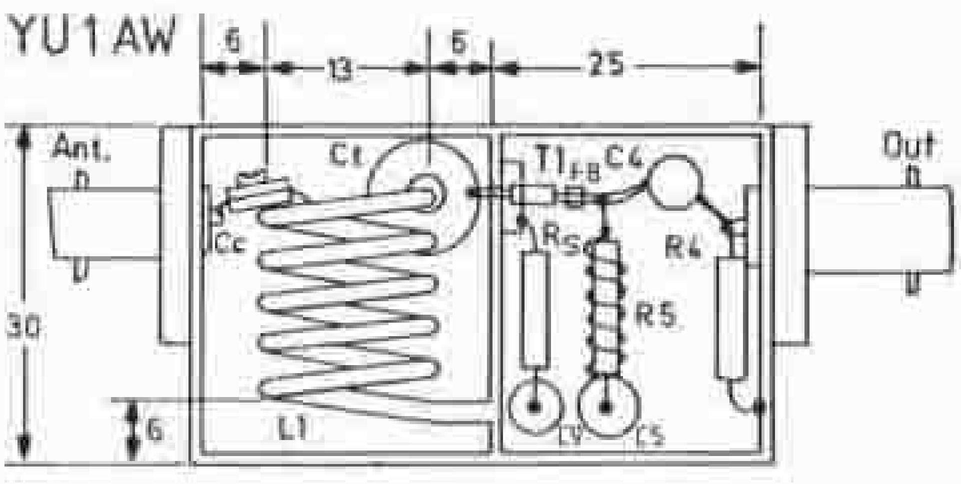

Fig. 10: Side-view of pre-amplifier constructed from fig.9

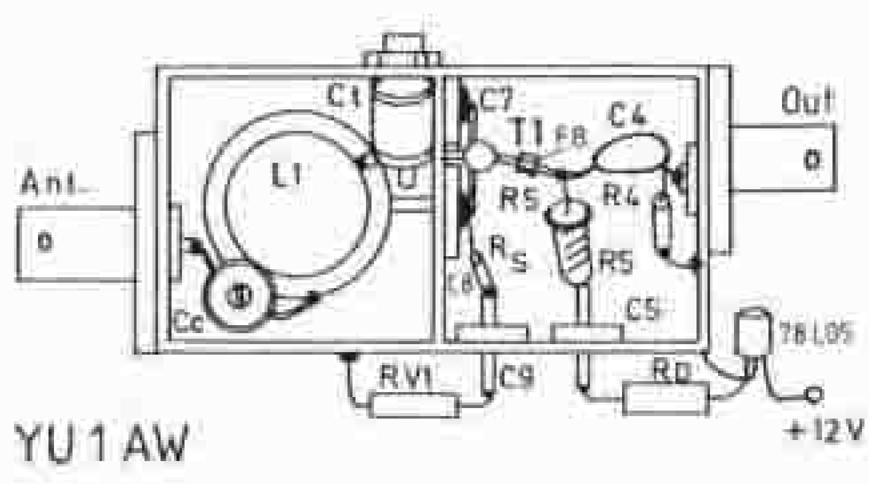

Fig. 11: Plan-view of pre-amplifier constructed from fig. 9

amplifiers are only stable in a very limited band of the input and output impedances and for this reason the peak values for gain and noise figure are often unobtainable. A resistance loading in the drain circuit reduces the superfluous amplification and brings the FET in a stable working region. A ferrite bead slipped over the drain lead also helps to improve the stability.

The amplification may also be adjusted in this amplifier by varying the values of R4 and C4. The drain current I_D may be adjusted by the preset potentiometer RV1 which is mounted outside the screened housing. This method is convenient and can also be used for the BF 981 pre-amplifier described earlier.

The only difference between the MGF and the CFY types (besides the lead arrangement) is the drain source voltage V_{ds}. The MGF types require 3 V and the CFY types 4 V. R_D must have a value of 10 Ω.

The results achieved also conformed very well with the calculations. The input losses lay at about 0.15 dB – a little higher than the BF 981 amplifier. The reason for the higher loss lay in the unfavourable input impedance of the GaAsFET. This resulted in a higher value for Q_l so that, for a given value of Q_u, the losses have to be higher.

The input losses with the CF 300 could only be minimised to 0.36 dB and they could be very much higher if the proper care is not taken.

The importance of the input circuit quality is made evident in table 2. It contains a comparison of a few common input circuits extracted from general literature and completed with a few proprietary pre-amplifiers.

3.1. Components List

C_i:	1.5 - 5 pF trimmer cap. (Johanson)
C_c:	1.5 - 6 pF ceramic or PTFE cap.
C 3:	2 - 10 pF ceramic or PTFE cap.
C 4:	25 pF disk cap.
C 5, C 9:	1 nF feedthrough cap., solderable
C 6, C 7, C 8:	1 nF disk cap. without connection
RFC:	12 turns Cul wire, 0.2 mm on R 5
L 1:	D = 13 mm; L = 18 mm; silvered wire, 2 mm Ø
L 2:	D = 6 mm; L = 15 mm; n = 5 Cul wire, 1.5 Ø

4. SUMMARY

Upon the basis of theoretical proof and practical research, it has been shown that it is feasible to employ low-noise transistors more efficiently in low-noise pre-amplifiers. Helical resonators instead of normal coils result in a higher unloaded Q

3.2. Explanation to Table 2

No.	Type	D (mm)	L (mm)	n	d (mm)	Note
1	coil	14	18	5	2	helical coil without shield
2	helical res.	14	18	5	2	resonator 25 x 25 x 30 mm
3	coil	9.5	12.7	5	1.2	published in magazine
4	coil	4.8	12.7	9	0.6	published in magazine
5	same as no. 1					
6	same as no. 2					
7	same as no. 3					
8	coil	9	18	6	1	published in YU-VHF-Magazine
9	coil	7	15	6	1	published in magazine
10	same as no. 1					
11	same as no. 2					
12	coil	6	12.7	8	1	published in magazine

(Q_u). By careful arrangement of the input circuit and the choice of the transistors, very low values of loaded Q (Q_l) were achieved and thereby very low input matching circuit losses. The losses result directly in a low-noise figure for the pre-amplifier. The above described pre-amplifiers represent, in this respect, a worthwhile improvement upon previously published designs.

5. LITERATURE

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