RF CIRCUIT DESIGN — 2

Do you get annoyed from time to time (or more often) by your favourite FM radio programme being interrupted when a strong out-of-band signal blocks the receiver? If so, read this article and find out how to design and construct a filter that may ban this irritation for ever.

VHF FILTERS

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Elektor Electronics has presented its readers with comprehensive articles on theory and practice of VHF aerial amplification before: see, for instance, the February 1980 (UK) issue of this magazine. The conclusions reached in those articles may be summarized as follows:

1. A well-designed aerial amplifier can only compensate for cable loss if it is mounted in the immediate vicinity of the aerial (masthead mounting).
2. To be of any beneficial use at all, this booster must have appreciably lower self-generated noise than the receiver.
3. The first active device in the receiver RF signal chain determines to a large extent the total receiver system noise figure and thus its sensitivity for weak signals.
4. A good directional aerial is the best booster because it generates no noise, is absolutely intermodulation-free and functions as a selective device at the same time.

As evidenced by the article on the wideband aerial booster with Type BFT66 transistor, low noise, good intermodulation ratio and high signal gain are generally appreciated characteristics of active devices in VHF aerial amplifiers. However, it was also pointed out that only one of these characteristics may be favoured over the others given a certain transistor working point; the three are never optimum for one bias setting.

It is for this reason that many wideband amplifier designs use two identical, cascaded *high fr* type transistors; the first (aerial side) set for low noise, the second (receiver side) for high overall gain. It will be fairly obvious that intermodulation characteristics of such a design are far from ideal, simply for lack of suitable DC setting and appropriate filtering. To increase bandwidth and reduce the intermodulation products, these transistors are usually direct-coupled, and every effort has been made to keep booster gain as high and constant as possible over a frequency range as large as 50. . . .800 MHz.

It will stand to reason that this type of amplifier can not be used for reception of weak FM band signals, because the odds are that a far stronger RF signal present outside the receiver tuning range will wreak havoc with the booster transistors. Even if the aerial features some attenuation for this out of band signal, booster input voltages may be as high as 100 mV with a powerful transmitter in close proximity. Even a very selective and intermodulation-free receiver can not do anything towards improvement of reception in this case, simply because it sees a mess of interference and intermodulation products at its input.

To keep strong out-of-band signals away from the base of the VHF preamplifier stage, some filtering device is called for. Conflicting design considerations contend for the upper hand, however, and a basic knowledge of filter operation and construction is required to find

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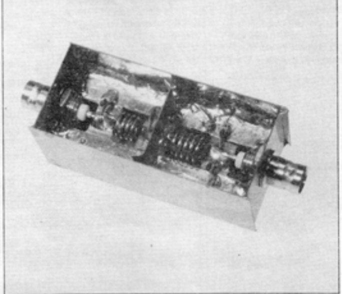

Photograph 1. Practical realization of the VHF roofing filter LPF section. Though its characteristics are not ideal, it provides a good starting point for more advanced filter construction. Note the two capacitors at the input; their total capacitance should be about 44 pF.

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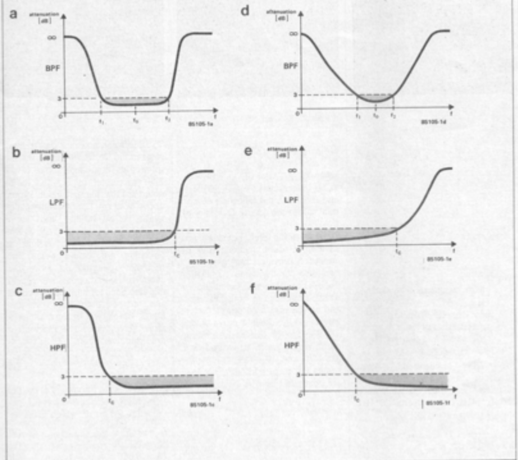


Fig. 1. Typical curves showing that a band-pass filter (BPF) profile is obtained from adding curves of constituent low pass (LPF) and high pass (HPF) sections.

the right compromise for a given situation.

VHF filters; a crash course

For a basic understanding of filter operation, it is useful to think of it as a sieve; depending on the diameter of its holes, it will pass the desired liquid and block large particles, however many. In electronics, such a sieving device is generally referred to as a **band-pass filter**; it has a high **attenuation** for all signals outside its **pass band**.

A typical frequency vs attenuation curve of a bandpass filter (BPF) is shown in Fig. 1a. The shaded area is referred to as the filter **3dB bandwidth**. Note that Fig. 1d also shows a BPF curve, but this time with lower **skirt steepness** than that of Fig. 1a, and a reduced 3dB bandwidth. From this comparison of filter curves it should be evident that the term **filter selectivity** it not related direct to 3dB bandwidth.

Although the band-pass filter type is a suitable starting point for introducing filter theory, it must be mentioned here that it is basically a combination of two constituents: a low-pass filter (LPF) and a high-pass filter (HPF), the curves of which are shown in Figures 1b and 1c respectively. Note that skirt steepness of both LPF and HPF may be less, as shown in corresponding Figures 1e and 1f. It will be evident that the BPF curves of Figures 1a and 1d may be obtained by adding Fig. 1b to 1c and Fig. 1e to 1f respectively.

To define the 3 dB bandwidth of the BPFs, it will be seen that

BPF f_1 = HPF f_c and (1)
BPF f_2 = LPF f_c (2)

where f_c is the **cut-off frequency** of LPF or HPF, or the frequency at which the filter output, U_o, falls to

$U_o = 0.708 U_i = \frac{1}{2}\sqrt{2} U_i = 3$ dB attenuation (3)

Thus, the 3 dB bandwidth of a BPF may be calculated from

$bw_{3dB} = f_2 - f_1$ <Hz> (4)

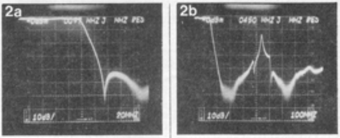
The curves shown in Fig. 1 are theoretical and therefore idealized; depending on component tolerance and construction method of the filter, it may feature far less smooth characteristics, as will be seen later. Neither need band-pass curves always be symmetrical like those of Fig. 1; depending on skirt steepness of constituting LPF and HPF, the low and high side **roll-off characteristic** of a BPF may have quite different profiles.

To come to a conclusion about suitable electronic components for use in filters, the low-pass setup shown in Fig. 2a may be examined; it is also known as a 'pi type' (note its visual similarity to π).

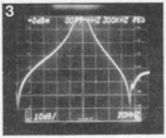
Assuming that the circuit is at resonance, that $R_i = Z_i = Z_o = R_o = Z$ and that Q (quality factor) is fairly high, then the basic design equations for this filter are as follows:

$$Z \approx \sqrt{\frac{L}{C}} \qquad (5)$$

Photograph 2. Roll-off characteristic of the VHF roofing filter LPF section (2a) and response of the same when swept over several hundred Megahertz (2b). Note that low attenuation corresponds to a high point in the curve, as opposed to the curves in Figures 1 and 2.



Photograph 3. Band-pass profile of the VHF roofing filter, sweep centre frequency at 97 MHz.



$$L = \frac{R}{\pi f_c} \qquad (6)$$

$$C = \frac{1}{\pi R f_c} \qquad (7)$$

$$f_c = \frac{1}{2\pi\sqrt{LC}} \qquad (8)$$

where

R = filter termination resistance <Ω>

L = inductance in filter <H>

C = capacitance in filter <F>

f_c = 3 dB cut-off frequency <Hz>

Z = filter impedance <Ω>

For VHF applications, these equations are adapted as follows to calculate with nH (nano Henry, 10^{-9} H), MHz (mega Hertz, 10^6 Hz), and pF (pico Farad, 10^{-12}F):

$$Z \approx \sqrt{\frac{1000L}{C}} \; <\Omega> \qquad (9)$$

$$L = 159.2R/f_c \; <nH> \qquad (10)$$

$$C = 318\,000/Rf_c \; <pF> \qquad (11)$$

Example: if a filter of this type were to be constructed for f_c = 100 MHz, and Z = 50 Ω, the following component values are found: C = 63.6 pF, L = 79.6 nH.

To improve the filter skirt steepness, several of these sections may be cascaded provided they have been designed for the same termination impedance. However, so-called m-derived sections at both LPF input and output may be a more efficient way to get the desired curve shape; see Fig. 2b for the basic arrangement. With L and C calculated from (9), (10), and (11), the component values for these additional sections are computed from

$$L_1 = mL \qquad (12)$$

$$C_1 = \frac{1-m^2}{4m}\,C \qquad (13)$$

$$C_2 = mC \qquad (14)$$

To understand how m is determined, refer to Fig. 2c which shows the frequency vs attenuation curve of the filter proposed in Fig. 2b. To be noted are the 'humps' which appear above f_c; at f_∞, the filter attenuation seems to be infinite, and this is repeated at regular intervals as f increases. The points of infinite attenuation are called **poles** and, generally speaking, the more filter sections, the more poles will appear; this also goes for high-pass sections, and, consequently, for band-pass filters which will feature poles at either side of the curve. The value of m is calculated from

$$m = \sqrt{1 - f_c^{\,2}/f_\infty^{\,2}} \qquad (15)$$

where f_∞ is the frequency of the first pole. Most designers, however, use the value 0.6 for m, which gives us

$$L_1 = 0.6L \qquad (16)$$
$$C_1 = 0.27C \qquad (17)$$
$$C_2 = 0.6C \qquad (18)$$

for the three-stage LPF of Fig. 2b.

There are several types of m-derived sections, and some of them are shown in Fig. 3. To go into the design calculations for the components in these sections would be beyond the scope of this article, and interested readers are referred to the numerous handbooks on this subject.

VHF roofing filter

A practical example will no doubt be quite helpful at this stage; if only to get an idea of the practical problems involved in filter design and construction.

Figure 4 shows the circuit diagrams of precisely calculated filters with m-derived sections shown in Fig. 3. If the proposed LPF and HPF are cascaded, a band-pass filter may be obtained with suitable characteristics for selective VHF reception (85... ...110 MHz). Note the component values in LPF and HPF; they are, of course, theoretical. The term **roofing filter** is used to refer to the protec-

Fig. 2. Starting from the basic **pi**-LPF (Fig. 2a), **m**-derived sections may be added (Fig. 2b) to obtain a low pass profile as shown in Fig. 2c.

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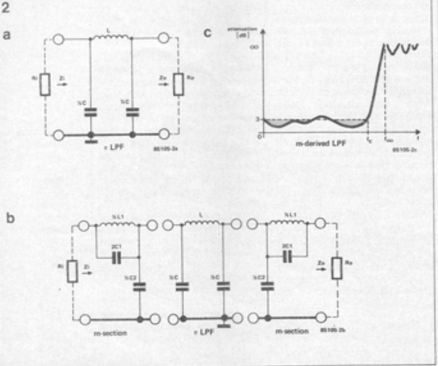

tive (i.e. selective) character of this device, which is intended to keep strong out-of-band signals away from the first active device in the aerial booster, for reasons outlined above. Prototypes were made of these sections, and the LPF is shown in Photograph 1. Note the RF-tight construction in a brass enclosure and the short capacitor lead lengths to avoid stray inductance. The frequency curves of this LPF were examined with an RF sweep generator; Photograph 2a shows the roll-off characteristic and the first pole at about 130 MHz. Skirt steepness looks quite acceptable, and so does the pass-band attenuation; so far, so good. Sweeping the filter over a larger frequency range, however, reveals a quite unexpected peak in the UHF area; at 490 MHz, filter attenuation is only 13 dB, or about 5 times. As this frequency lies within TV band 4, there may still be trouble with a local transmitter despite the fact that the filter 'looks good' when swept over its target frequency range.

The rather disappointing results of these measurements, however, are still useful because we should be on our guard when looking at beautifully symmetrical curves of filters with low pass-band insertion loss, high Q factor, and near-perfect input and output matching; there are bound to be ugly peaks at frequencies well removed from the filter design frequency.

To finish this paragraph, Photograph 3 shows the impeccable band-pass curve of the roofing filter consisting of cascaded LPF and HPF to the designs of Fig. 4. Note the near-symmetrical profile and 3 dB bandwidth of about 25 MHz. Finally, it must be mentioned that the undesirable out-of-band peaks are mainly caused by the rather unpredictable, complex impedance of the filter for frequencies outside its pass-band range. Furthermore, the choice of capacitors plays an important role, so constructors who have read the following paragraphs may use the information given to produce a better version of this filter.

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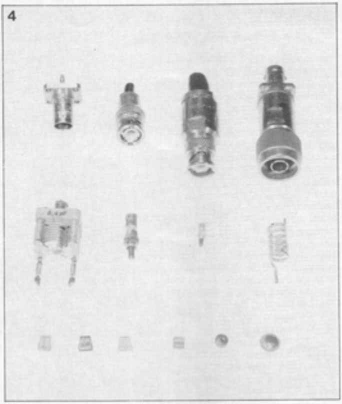

Photograph 4. A look at some filter components; upper row: BNC type socket and plug; BNC plug for 10 mm diameter coax cable; home-made N-to-BNC adapter. Middle row: split stator (butterfly) trimmer; ceramic tubular trimmers — chassis and PCB mount types; VHF coil. Lower row: leadless capacitors (chip types).

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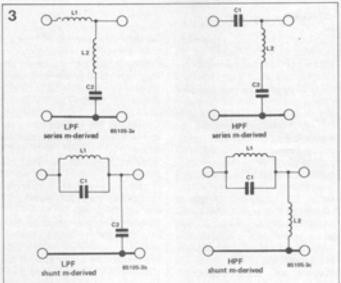

Fig. 3. These are some of the simpler configurations for m-derived sections.

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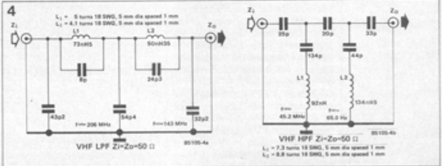

Fig. 4. Circuit diagrams and coil winding data for LPF and HPF which, when cascaded, form a VHF roofing filter. Note that the filters use m-derived sections shown in Fig. 3.

Filter matching

Filter design theory generally assumes ideal impedance matching at input and output. However, effects like out-of-band peaking can hardly be calculated because there are too many unknown variables involved.

For a strong out-of-band signal, a four-element VHF Yagi type aerial has a very unpredictable impedance, and so has the filter input.

The only known and stable impedance in the receiver RF chain is provided by the coaxial cable (50 or 75 Ω).

The undesired signal, then, will find the filter input as highly unmatched, and a large part of the signal will be reflected into the cable, only to be reflected again by the aerial. The delaying effect of the coax cable added to the unavoidable phase shift and reflection cause a so-called **standing wave.** It will stand to reason that the filter input must be as **reflection-free** as possible for the desired frequency band, simply because a large part of the RF signal would else be lost to the active device. Furthermore, **filter insertion loss** must also be as low as possible, but, as we have seen, good band-pass profiles require many filter sections and thus many components to pass the signal, and neither of these has ideal (low-loss) characteristics.

A total filter insertion loss of 0.5 to 1 dB is already a good figure, but it should be kept in mind that **any** insertion loss adversely affects the optimum noise figure of the active device coupled to the filter output.

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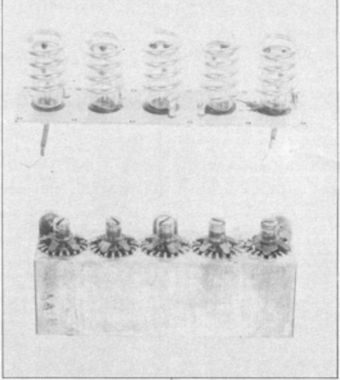

Photograph 5. This is a 5-stage helical filter for use in the 400 to 500 MHz frequency range. Coils are inductive-coupled and tuned with brass precision screws. Note the low-impedance tap at input and output coil.

Filter construction

To conclude this article, some useful suggestions will be given for the choice of filter components and mechanical construction, because it ought to be clear by now that good filter calculation may be useless if the practical realization is not up to the 'VHF standard'. As these are mostly unwritten laws, it is very instructive to have a look at some of the established VHF construction methods in, for instance, a discarded VHF/UHF TV tuner.

Coils: Use 20 SWG or thicker silvered copper wire (CuAg) for the self-supporting, air-cored coils, and make sure that coils in separate filter sections can not 'see' each other to avoid unwanted stray coupling. In case the coils are PCB mounted, coupling can be avoided by positioning them at an angle of 90°. There are, however, also filter types that are based on inductive or capacitive coupling of coils to achieve a suitable bandwidth, e.g. helix type narrow band slot-coupled filters, in which case the above rule does not apply.

Capacitors. To arrive at the calculated cut-off frequency, the capacitors must be close tolerance types (1 or 2%) with good high frequency characteristics (NP0 or silver mica). Keep leads as short as possible to avoid introducing stray inductance in the circuit; where available, ceramic chip capacitors are the ultimate solution. Trimmers, if used, are preferably tubular glass or ceramic types with extremely low end capacity (1 pF or less); older types of TV tuner still contain them in abundance, but they are not easy to get out intact.

Connectors. Use standard 50 Ω plugs and sockets such as those in the UHF series (PL259-SO239). BNC or N types are even better, however, and much to be preferred. Do not ask for trouble by using the cheap coax connections as used with modern TV sets and FM tuners.

Housing. The filter should be fitted in a stable metal housing (diecast box) to prevent strong signals from bypassing. If at all possible, fit the amplifier in a separate housing and connect it to the filter output with a short length of low-loss coax cable fitted with BNC or N plugs; this also goes for the aerial-to-filter connection. Phograph 4 shows some preferred parts for VHF filter construction, and, finally, Photograph 5 shows a UHF type band-pass filter for professional use.

Next time

A further instalment in this series will concentrate upon an up-to-date VHF preamplifier stage constructed on the universal HF board. JB:JB

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