Colour-sound system design

Providing coloured illumination as functions of sound frequency and intensity

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The compact system to be described for construction provides coloured illumination of a reflecting or opalescent surface, the brightness and colour being functions of the frequency and amplitude of an audio input. The circuitry is based on the 741 op-amp and its dual version the 747. Triacs control the mean lamp power which is a maximum of approximately 2kW for each of three channels.

The sound intensity and light intensity correlation of a colour-sound system is based on the premise that related simultaneous sensory activity of ear and eye will produce a reaction to which most people will be sympathetic. The relationship between pitch and colour (that is between the frequencies of sound and light) is not at all critical, probably because of the very different responses of the brain to these phenomena—few people, except possibly physicists, consciously relate colour to frequency.

Other systems are possible. For example, a sound intensity/colour correlation may be sought, coupled with a pitch/light intensity correlation. Whilst the author is not aware of any published work in this field, it is likely that aesthetic appreciation of such a system would require a considerable training programme. This would necessarily severely restrict the enjoyment of an untrained majority of observers.

A gate pulsing arrangement is used for each controlling triac which relates the firing angle to the instantaneous peak output voltage from the appropriate filter. In this way the conduction angle is closely proportional to the sound intensity, resulting in a good correlation between brightness and sound intensity. Tungsten filament lamps form the light sources. Fluorescent tubes could be used as an alternative.

Design philosophy

A block diagram of the colour-sound system and the waveforms at the various points in the system are shown in Figs. 1 and 2.

The incoming mains voltage (V_1) is squared (V_2) and integrated to provide a linear time varying voltage (V_3) in each half cycle. This is compared with the peak rectified filter output voltage (V_4) to advance or retard the triac firing angle α in sympathy with the amplitude of the audio input to the filter. Voltage V_4 is arranged to increase towards zero from $+10$V for control during the positive mains half cycle and from -10V during the negative mains half cycle. The output from the level detector (V_5) is arranged to rest at zero volts when

$$(-12 + V_4) < V_3 < (12 - V_4) \qquad (1)$$

to be $+10$V when

$$V_3 > (12 - V_4) \qquad (2)$$

and to be -10V when

$$V_3 < (-12 + V_4) \qquad (3)$$

The positive and negative edges occurring at the times set by the above relationships (2) and (3) initiate narrow pulses (V_6) which fire the triac appropriately.

Three channels are used to cover the frequency ranges below.

Bass:	30Hz–125Hz
Mid:	125Hz–500Hz
Treble:	500Hz–2000Hz

These frequency ranges cover adequately the range of fundamental frequencies in music. The rest of the audio spectrum above 2000Hz carries principally harmonic information for aural identification

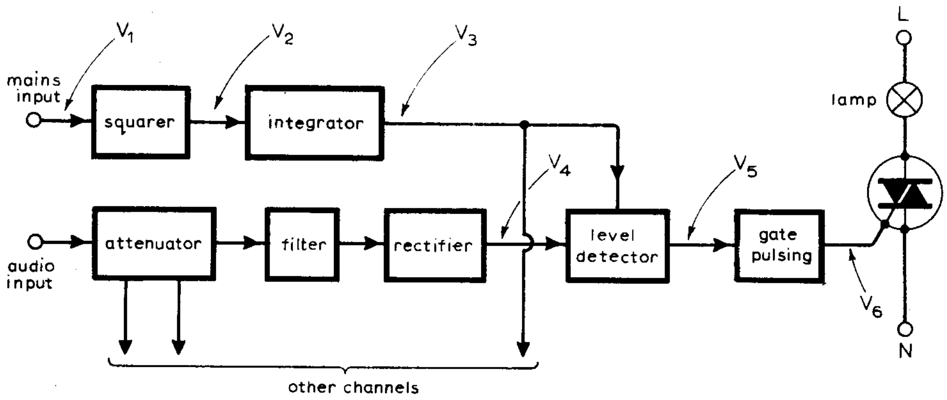


Fig. 1. Block diagram of one channel of the colour-sound system. See Fig. 2 for the waveforms marked at V_1, V_2, etc.

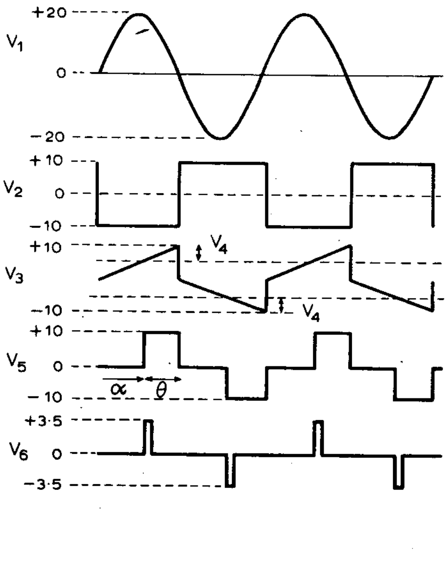


Fig. 2. Waveforms at the points indicated (V) in Fig. 1. See text for full explanation.

of particular instruments. The lower limit of the bass range is judged to be a reasonable compromise between adequate bass instrument coverage and the exclusion of mechanically originated signals such as turntable rumble. Harmonics from the bass and middle range tones of instruments cannot be excluded from the filter if they lie within the pass band. Subjective tests with various types of music indicate, however, that no serious problems arise from these harmonics.

Circuit description

The circuit diagram is shown in Fig. 3.

The filters are low pass/high pass combinations based on the voltage controlled source (v.c.v.s.) circuit. The requirement for this application is to have no pronounced peaks in the response curves of either the low or the high pass sections (see Appendix).

The filter output rectifier is of conventional design and provides two symmetrical outputs. Under no-signal conditions the outputs settle to potentials $\pm V_B$ close to ± 10V, determined by R_{15}, R_{16} and R_{17}. Voltage V_3 sets a minimum conduction angle for the triac and so provides a minimum brightness facility. This is desirable to ensure that lamps respond visibly to small input signals. Trimming is provided by R_{26} which controls the slope of the integrator output. Alternatively R_{17} may be made a preset resistor, but integrator slope control has the advantage of taking up the tolerance in the feedback capacitor. Resistors R_{13} and R_{14} are included to limit the maximum output current from the amplifier to a safe value. Time constants C_7R_{15} and C_8R_{16} are chosen as a compromise between reasonable smoothing of the lowest audio frequency and rapid decay so that musical transients are tolerably handled.

An amplifier with a non-linear feedback loop comprising zener diodes D_{11} and D_{12} squares the transformed mains waveform. The zero-resetting integrator time constant $C_{12}(R_{26} + R_{27})$ is calculated from

$$V_3 = (1/C_{12}R_T)\int_t^0 V_2 dt$$

where V_3 is the integrator output, V_2 the input square wave, and $R_T = (R_{26} + R_{27})$. With ± 12V supplies, a 741 amplifier has a useful output voltage range of ± 11V. Hence, $V_3 = 11$V at $t = 10$ms. Therefore

$$11 = V_2/C_{12}R_T \times 10 \times 10^{-3}$$

$$C_{12}R_T = 0.91 \times 10^{-3} \times V_2.$$

But $V_2 = 10$V so $C_{12}R_T = 9{\cdot}1$ms, and C_{12} is made 0·1µF and R_T 91kΩ.

Resistor R_T is conveniently formed by a series combination of 68kΩ and a preset 50kΩ. Transistor Tr_1 or Tr_2 is pulsed momentarily at the end of the mains half cycle to discharge C_{12} rapidly through R_{30}. Which transistor is pulsed depends on the direction of the square wave edge and it is arranged that the transistor with the appropriate collector polarity at this time turns on. The emitters are at earth potential because of the virtual earth property of the amplifier.

Resistor R_{30} limits the capacitor discharge current to a safe value for Tr_1 and Tr_2 but still provides a very short discharge time constant.

Diodes D_{13} and D_{14} prevent spurious reverse bias effects of Tr_1 and Tr_2 affecting the integration.

Transistors Tr_1 and Tr_2 must conduct for long enough to fully discharge C_{12} but for a short time compared with the mains half cycle duration of 10ms.

Assuming $R_{SAT} = 0$ for Tr_1 and Tr_2, C_{12} will discharge in approximately $5C_{12}R_{30}$ secs. Inserting values yields a discharge time of

$$t = 5 \times 0.1 \times 330 \times 10^{-6} = 165 \text{ µs}.$$

Allowing 200µs for safety, C_{11} can be estimated from a knowledge of the base-emitter resistance R_b of Tr_1 and Tr_2. The calculation will be approximate because of the non-linear nature of R_b, and the natural spread of this parameter between transistors. Resistors $R_{28,29}$ limit the peak base current.

Assuming $R_b = 3$kΩ and a base turn-on voltage of 0.7V, then the turn-off potential is $(4/3) \times 0.7 = 1$V. Therefore

$$1 = V_2 \exp(-t/C_{11}R) \text{ where}$$

$R = R_b + R_{28}$ and the applied square-wave amplitude, V_2, is 10V. Then,

$$C_{11} = t/R \log_e 10 = 22\text{nF}.$$

A standard 22nF capacitor suffices for C_{11}. Care must be taken not to make C_{11} too large since it prolongs transistor conduction and impairs the integration waveform.

The two outputs from the rectifier are compared with the integrator output using the differential input facility of the 741 amplifier.

For amplifier 3, diode D_5 holds the output (V_5) at $+10$V unless the integrator output (V_3) voltage is greater than the appropriate (positive) filter rectifier output (V_4).

When $V_3 > V_4$, V_5 falls to a value $V_4 - V_z$ where V_z is the zener voltage of D_6.

A similar result but inverted is obtained

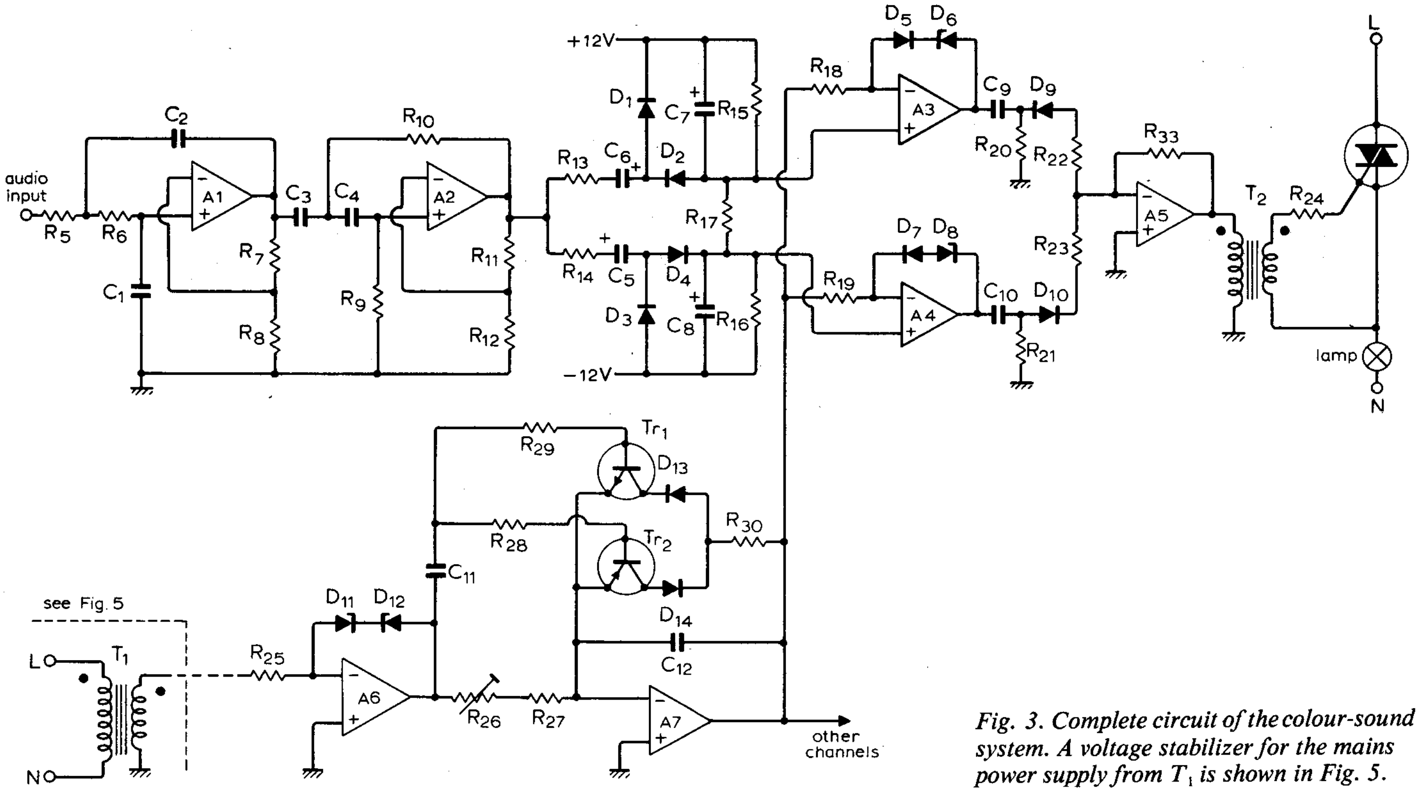


Fig. 3. Complete circuit of the colour-sound system. A voltage stabilizer for the mains power supply from T_1 is shown in Fig. 5.

from amplifier 4 when the negative rectifier output falls below V_4, in the negative half cycle.

Resistors R_{18} and R_{19} provide the zener current and should not be large. A value of 1kΩ is satisfactory.

The networks C_9, R_{20}, D_9 and C_{10}, R_{21}, D_{10} provide short negative and positive pulses respectively generated from the leading edges of the level detector outputs. These are summed and squared by amplifier 5 which provides gating pulses to the triac.

Transformer coupling to the triac (T_2 in Fig. 3 and T_{2-4} in Fig. 8) is used to provide isolation of the control circuitry from the mains.

It is useful to have a separate manual gain control for each channel. Since the audio input comes from a low-impedance (i.e., loudspeaker terminals) a simple network such as that in Fig. 4 gives excellent results.

The current demand per channel is approximately 20mA. A regulated power supply based on zener diode stabilization of the base of a transistor is shown in Fig. 5.

It is desirable when using linear i.cs to decouple the supply rails close to the amplifier. Capacitors C_x of value 0.1μF are used for this as shown and are placed close to the filter amplifier in each channel, and close to the integrator.

Triac circuitry and layout

Triacs are constructed usually with the A_2 anode in contact with the heat sink. To simplify the mounting of the three triacs a single heat sink is used and all anodes are thus in contact. The lamps are placed in the A_1 anode leads and the gating transformer secondaries connected between gate and A_1 anode. The electrical arrangement appears in Fig. 6.

The main system (filter channels, resetting integrator and power supply) are conveniently laid out on a single 0.1in pitch stripboard. The prototype main system used single 741 amplifiers and was laid out as in Fig. 7. The input attenuator, triacs, mains transformer, input and output sockets are mounted separately to suit the installation. The prototype used the layout in Fig. 8.

Lamps and displays

The triacs specified are capable of handling up to 8A r.m.s. which corresponds to approximately 2kW per channel. Filament lamps of this order of power tend to have long thermal time constants and do not follow a sound intensity pattern as well as do lamps of lower power. Very satisfactory results are obtained with filament lamps up to 150W. Three of these are considered adequate for a domestic installation (i.e., one per channel). For larger installations in dance halls, discos and exhibitions, banks of 150W lamps are recommended.

The author has found it more satisfactory to use a reflecting surface than a transmitting opalescent medium for display since attention tends to be drawn

Components

Resistors—*R*

1	100 lin 1W	11, 12	10k
2, 3, 4	1k lin $\frac{1}{2}$W	13, 14	470
5	12k low range	15, 16	22k
	3.3k mid range	17	150k
	820 high range	18, 19	1k
6	12k low range	20, 21	2.2k
	3.3k mid range	22, 23	10k
	820 high range	24	47 $\frac{1}{4}$W
7, 8	10k	25	6.8k
9	56k low range	26	50k lin preset
	12k mid range	27	68k
	3.3k high range	28, 29	1k
10	56k low range	30	330
	12k mid range	31, 32	560
	3.3k high range	33	100k

All resistors $\frac{1}{8}$W 5% unless stated otherwise.

Capacitors—*C*

1, 2, 3, 4	0.1μ ±20%	12	0.1μ ±20%
5, 6, 7, 8	10μ/25V	13, 14	1000μ/25V
9, 10	0.1μ ±20%	*x*	0.1μ ±10%
11	22n ±20%		

Diodes—*D*

1–5	OA200	11, 12	BZY88–C9V1
6	BZY88–C9V1	13, 14	OA200
7	OA200	15, 16	OA210
8	BZY88–C9V1	17, 18	BZY95–C12
9, 10	OA200		

Transistors—*Tr*

1	BC108	3	AC176
2	2S303	4	AC128

Triacs

All MAC11

Op amps

All 741 8-pin d.i.l.

Sockets—*SK*

1, 2, 3	2-pin 250V 5A	4	jack

Transformers—*T*

1	Radiospares 12V miniature
2, 3, 4	primary 300mH and <5Ω turns ratio 3:1. Insulation to withstand 1000V flash test between prim. and sec.

Suppression

R_s	47 $\frac{1}{4}$W
C_s	0.05μ/400V
L_s	0.2mH non-saturating up to full load current

Heatsinks, switch, stripboard

Triac sinks—aluminium
150mm × 40mm × 16 s.w.g.
Tr_3–Tr_4 sinks—aluminium
80mm × 40mm × 16 s.w.g.
Switch—250V, 5A
Stripboard—0.1in pitch 34-way

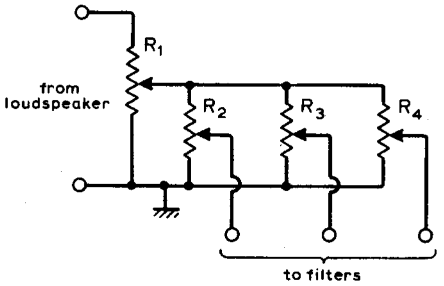


Fig. 4. Input attenuator which can provide separate manual gain control for each channel.

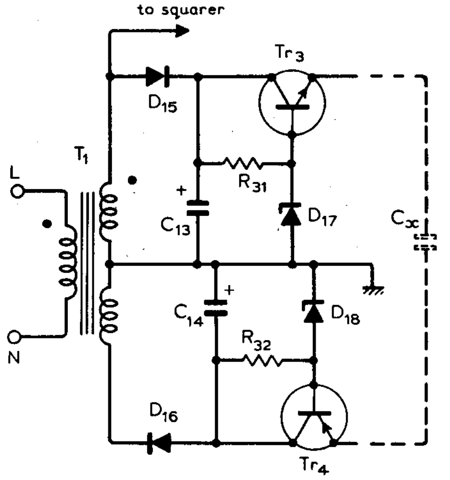


Fig. 5. Regulated power supply based on the zener diode stabilization at the base of a transistor.

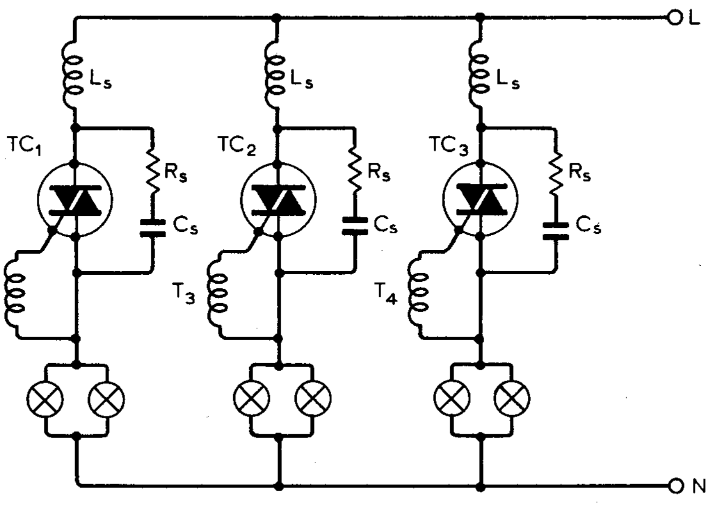
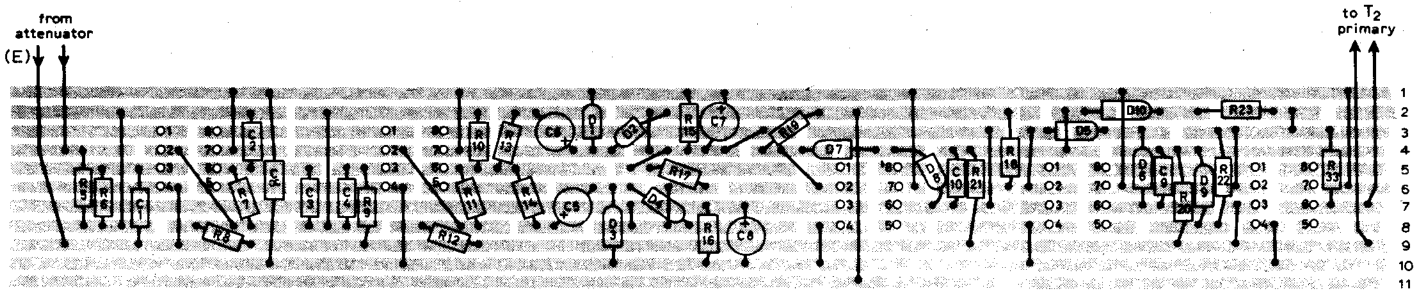


Fig. 6. Lamp and triac circuitry. Mounting the three triacs is simplified by using a single heat sink.



AMPLIFIER PIN CONNECTIONS

null (not used)	01	05	null (not used)
inverting input	02	06	output
non-inverting input	03	07	positive supply
negative supply	04	08	no connection

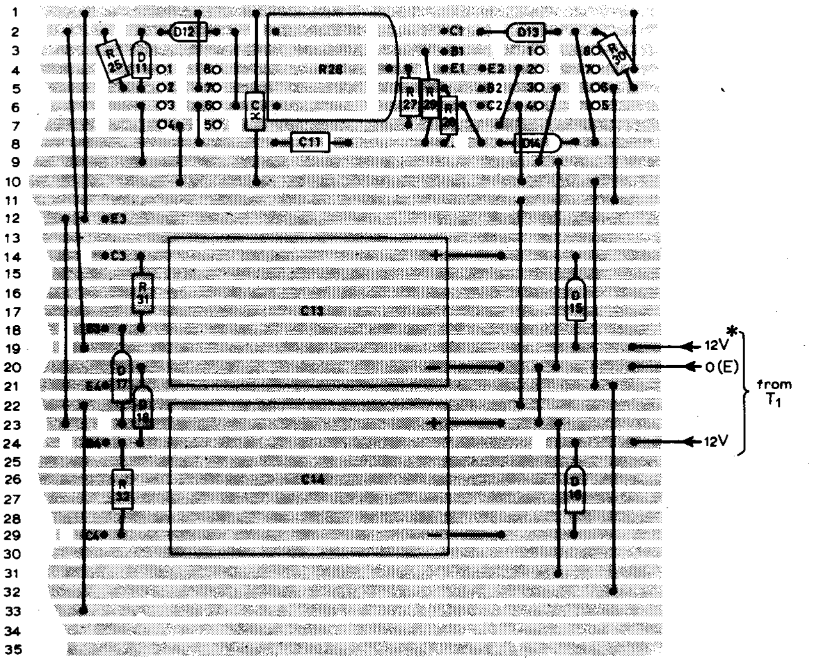


Fig. 7. Layout of one filter channel (top), resetting integrator and power supply from the component side. Strips 1–11 (top) are continuous to 35 (not shown) to facilitate the remaining two channels. These strips (1–35) are continuous with the lower diagram.
** 12V from T_1 secondary in phase with line (mains) input.*

to the brightest parts of a transmitting system, namely the lamp filaments. A simple but effective display for domestic purposes consists of three lamps mounted separately in ventilated boxes with gelatine colour filters on the fronts and aluminium foil reflectors behind the bulbs. Set about a yard apart and tilted upwards to illuminate a white or cream wall some pleasing results are obtained.

The rapid switching of triacs every half cycle gives rise to a wide spectrum of harmonics in the mains current waveform. These must be properly filtered to prevent interference with television reception. Present practice with lamp dimming circuits is to employ an r.f. choke/capacitor arrangement as shown in Fig. 6.

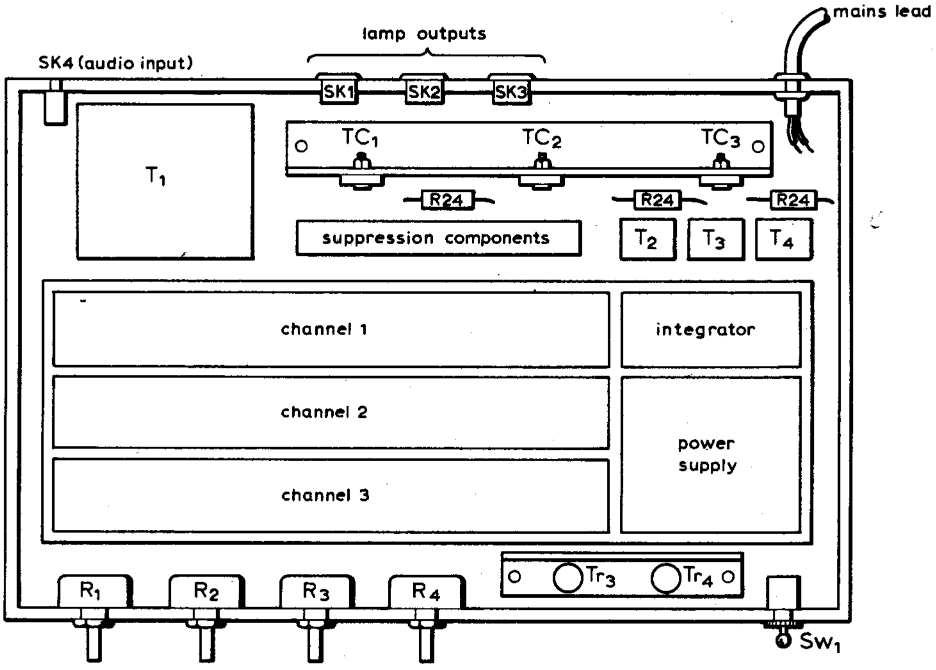


Fig. 8. Layout in the prototype.

Appendix

Filter design

The v.c.v.s. (Fig. 9) is chosen for this application because of its very high input impedance and low output impedance, and its tolerance of variations in component values.

Moreover, the parameter H_o (see below) in the filter transfer function is a free parameter equal to the v.c.v.s. gain constant K. This makes mid-band gain simple

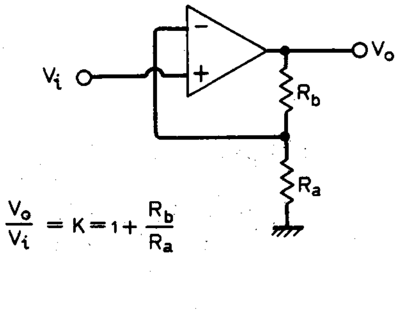


Fig. 9. Configuration of the voltage-controlled voltage source circuit.

to control for the cascaded sections. The design equations are:

$$V_o/V_1 = K = 1 + R_b/R_a$$

$$H_o = K$$

Low pass section:

$$R_6 = \frac{\alpha}{2\omega_0 C}\left(1 + \sqrt{\frac{1 + 4(H_0 - 2)}{\alpha^2}}\right)$$

$$R_5 = 1/\omega_0{}^2 R_6 C^2$$

High pass section:

$$R_9 = \frac{\alpha}{4\omega_0 C}\left(1 + \sqrt{\frac{1 + 8(K - 1)}{\alpha^2}}\right)$$

$$R_{10} = 1/\omega_0{}^2 R_9 C^2 \text{ where } \alpha = 1/Q$$

and ω_o is the undamped natural frequency of the two-pole filter.

The curves of Fig. 10 show the generalized responses for various values of K. From this it is clear that $\alpha = 1$ provides the type of response suitable for the present application.

The input voltage will be that appearing across the terminals of a loudspeaker. Adopting a nominal 2V r.m.s. for full brightness the overall mid-band gain of the filter should be, by assigning the same value K to each section and assuming a peak output of 11V from amplifier 2,

$$K^2 = 11/2\sqrt{2} = 3{\cdot}89.$$

This leads to a nominal K value per section of 2. Inserting these results in the above formulae gives:

low pass: $R_2 = 1/\omega_o C$ and $R_1 = R_2$

high pass: $R_1 = 1/\omega_o C$ and $R_2 = R_1$.

The procedure is now to choose C for convenience and calculate R_1 and R_2. Resistors R_b and R_a are chosen for a K value of 2 and for minimal output loading of the amplifiers.

The design of these sections has been such as to ensure overlap of responses between the three bands. Some frequencies, therefore, will excite responses from two adjacent lamps. Additive or subtrac-

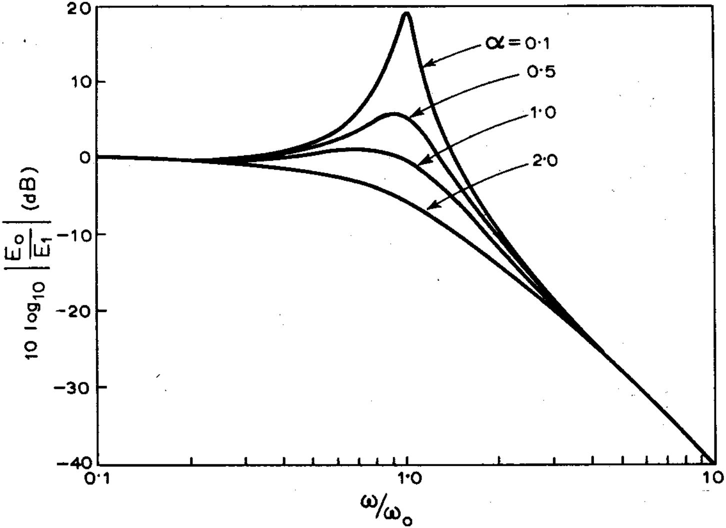


Fig. 10. Response curves for various values of $\alpha = 1/Q$*.*
The equivalent high pass case is given by ω_o/ω*.*

tive combinations of colours can be so produced to the requirements of a particular installation. Should wider band separation or different bandwidths be required for a particular application it is a simple matter to apply the above formulae. Only four resistors per channel need be altered to tailor responses to suit these requirements provided the 0.1µF filter capacitor value is unchanged.

Sound and light

Having been associated with the design and manufacture of "sound-to-light" units for some years, I was particularly interested in the "Colour-sound system design" by J. R. Penketh in the May issue. Mr Penketh says that he is not aware of any published work relating to the relationship between pitch and colour. While this subject is not easy to investigate, I have come across some references which may be of interest.

It would appear that the first publication on this subject was "Sound and Colour" by J. D. McDonald, published in 1869. In 1883, F. J. Hughes wrote a book entitled "Harmonics of Tones", suggesting a system of matching colours to notes, and in 1884 D. D. Jameson wrote "Colour Music", which proposed additional theories on sound-colour combinations. Building upon these theories, Professor Alexander Wallace, of Queen's College in London, began work on a note-to-colour matching theory, using a mathematical scheme for assigning colour to sounds. His version of the theory states:—

"Taking the spectrum band as the basis of all colours, there are two remarkable points of resemblance between it and the musical octave. The first of them is that the different colours of the one, and the different notes of the other, are both due to the various rates of vibration, acting on the eye or the ear . . .

. . . If we measure the rate of vibration at the first visible point at the red end of the spectrum, we shall find it is approximately one half of what it is at the extreme violet end. Now in music, as we all know, this relationship is the

Wavelength of light. Å	395	433	466	500	533	566	600	633	666	700	733	757	Invisible
Approximate colour	deep red	crimson	orange/ crimson	orange	yellow	yellow/ green	green	bluish green	blue/ green	indigo	deep blue	violet	
Musical note	middle C	C#	D	D#	E	F	F#	G	G#	A	A#	B	C_1
Frequency of sound Hz	256	277	298	319	341	362	383	405	426	447	469	490	512

same. If we take the first and last notes of the octave, the latter has nearly double the number of air vibrations and the first note of the new octave has exactly double. This is the case also with the spectrum band. So far as one octave is concerned, the lowest red stands for the first note of the octave and the highest violet for the 12th or last note . . ."

By the late 1800s, using these basic analogies, Rimington had conceived a complete sound-to-colour scale (reproduced here) which allowed him to translate musical scores into colour.

In 1925 Mary Hallock Greenewalt, a "colour musician" of the time, decided to challenge the, by now, classic theory of Rimington. She maintained that no sound finds an exact counterpart in any one colour. She also noted that few musical compositions excited the same sensations in every performer or listener. Her feeling was that colours should not be tied inflexibly to notes, but that each "colour organist" should be free to interpret for himself the colour composition of the music which he was playing.

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Sound and light

While reading the interesting letter from Mr McNaughton (July issue) it occurred to me that perhaps the most common association between colour and music, supported by the common use of terms such as "brightness" and "sparkling" in description, is likely to be a correlation of excitement. If this were so, perhaps a scale of colour temperature would fit experience better than Rimington's spectrum scale.

I must confess to having never experienced a colour organ but it seems clear to me that a bassoon is brown (almost mahogany!) in the lower register, a low trombone brown flecked with bright ridges, chunks of Beethoven are a glowing rusty orange (strings) with brighter colours introduced by the woodwind; flutes are yellow-white and the piccolo approaches blue-white, especially at close quarters. "Light" music is tinted (unsaturated) while green is difficult to find: perhaps I could force it on the oboe or clarinet. Green is also difficult to see among the orchestra, or in the radiation from an incandescent black body.

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