PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Millimetric Waveguide Systems [and Discussion]

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*Phil. Trans. R. Soc. Lond. A* 1978 **289**, 123-134
doi: 10.1098/rsta.1978.0051

*Phil. Trans. R. Soc. Lond.* A. **289**, 123–134 (1978) [ 123 ]
*Printed in Great Britain*

# Millimetric waveguide systems

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The propagation of electromagnetic waves in hollow conducting tubes (waveguides) is reviewed and the properties of the low-loss mode are considered. The practical realization of a trunk digital transmission system employing the low-loss mode has been achieved in a Post Office field trial over a route length of 14 km; the system has a potential capacity equivalent to 500000 telephone circuits or three hundred 625-line television channels in each direction of transmission. The design and installation of the waveguide used for the field trial are described, and the results of transmission tests over the frequency band 32–110 GHz are presented.

The wide frequency bandwidth available for transmission is subdivided into channels using appropriate filters, each channel providing a digital capacity of 500 Mbit/s. The carrier associated with each channel must be modulated by the digital signals before transmission, amplified and demodulated after transmission along one repeater section, and distortion removed from the digital signals ready for transmission over the next repeater section; techniques for carrying out these operations are outlined.

Eight channels were fully equipped and the results of tests on three of the channels are given. Digital colour television transmission has been successfully demonstrated over four of the channels connected in tandem thereby simulating a 57 km route.

## 1. Introduction

To date, all line-communication systems carrying commercial traffic employ two conductors to guide the electromagnetic wave which transmits the information; these conductors may be in the form of a pair of wires or a wire located axially inside a conducting cylinder, the coaxial pair. For high-capacity systems, a number of coaxial pairs are grouped together to form a composite cable; thus a cable system currently being installed for the Post Office will have 18 coaxial pairs assembled into a cable of overall diameter 78 mm, use frequencies up to 60 MHz and have a capacity of 86400 two-way telephone circuits. Cable systems of considerably greater capacity would use correspondingly higher frequencies necessitating reduced repeater spacing to offset the increase in cable attenuation, and the cumulative distortion from the larger number of repeaters could be prohibitive; the communication engineer therefore turns to waveguides which are well suited to very high frequency transmission.

As early as 1897, Lord Rayleigh showed theoretically that an electromagnetic wave could be guided through a tube provided the wavelength was shorter than a critical value (for a circular tube this critical wavelength is 3.41 times the tube radius), but not until the advent of centimetre-wave signal sources was it possible to use hollow conducting tubes of reasonable size for transmission. A circular waveguide used just below its critical wavelength can propagate freely only one field pattern; however, the loss is much too high for long-distance communication purposes, although acceptable for a distance of a few tens of metres such as occurs between a radio equipment and its aerial. As the frequency is increased however, other field patterns can be transmitted, one of which results in such a low loss that its use makes trunk waveguide systems practicable.

Waveguide systems, like other line systems, are not subject to the constraints on spectrum usage as applied to radio systems and typically can operate over the frequency band 32–110 GHz, gaseous absorption being eliminated by filling the guide with dry nitrogen. Thus one waveguide system can provide enormous transmission capacity equivalent to about 500000 telephone circuits or three hundred 625-line television channels in each direction which, on a main trunk route, is sufficient for the provision and growth of existing and new services until possibly the late 1980s. Moreover, because of the low transmission loss, repeaters can be widely spaced, every 20 km or so, with consequential low installation and maintenance costs.

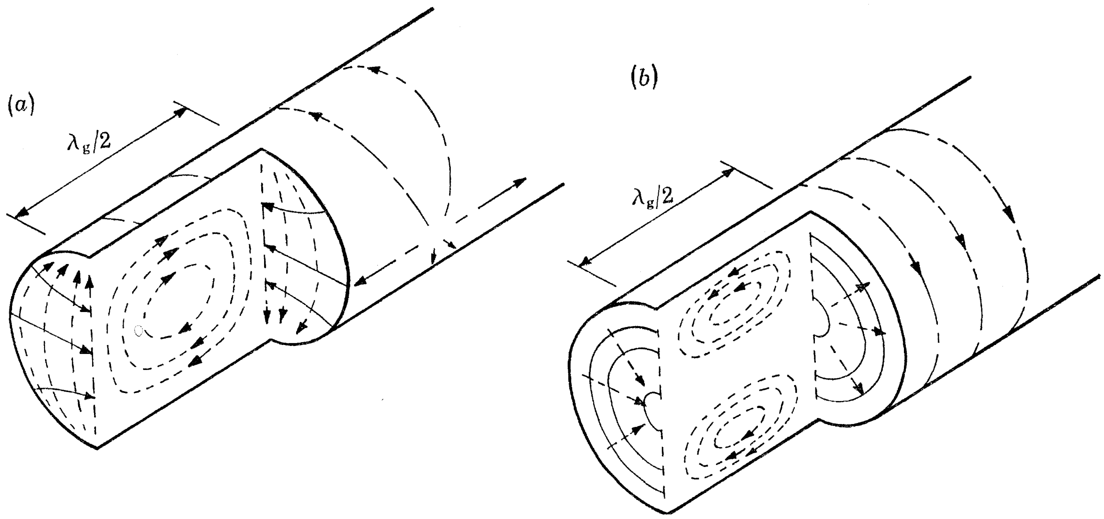


FIGURE 1. Field configurations of $TE_{11}$ (*a*) and $TE_{01}$ (*b*) modes in circular waveguides; $\lambda_g$ = guide wavelength.

## 2. The low-loss mode

Electromagnetic wave propagation within hollow circular conducting tubes can be determined by the use of Maxwell's equations, the various field components satisfying scalar wave equations. These wave equations have a multiplicity of solutions which determine the possible field patterns, or modes, that can be transmitted along the tube. As the frequency is increased just above that corresponding to the critical wavelength, only the dominant $TE_{11}$ mode field pattern of figure 1*a* exists; this mode is normally used for transmission distances of a few metres. At much higher frequencies large numbers of modes can be propagated; thus for a 50 mm diameter tube at 35 GHz about 90 modes can exist. Of these, the circular electric $TE_{01}$ mode with the field pattern of figure 1*b* has a very low loss, and this loss decreases steadily as the frequency increases (figure 2); Carson, Mead & Schelkunoff (1936) appear to have first discovered this mode. The low loss arises because no lines of electric intensity terminate on the wall so that there are no electric charges on the wall and no resulting wall currents; only circumferential wall currents associated with the magnetic field exist.

When a particular mode is transmitted for any distance along a waveguide it is difficult to maintain mode purity if other modes can propagate. If, for example, there is a slight step at the junction of two lengths of waveguide, then spurious modes must be generated to satisfy the electromagnetic boundary conditions over the complex surface at that junction. A continuous perturbation of the waveguide surface, bending the waveguide for example, can likewise cause energy to be coupled from a wanted mode to an unwanted mode and possibly back to the wanted mode again.

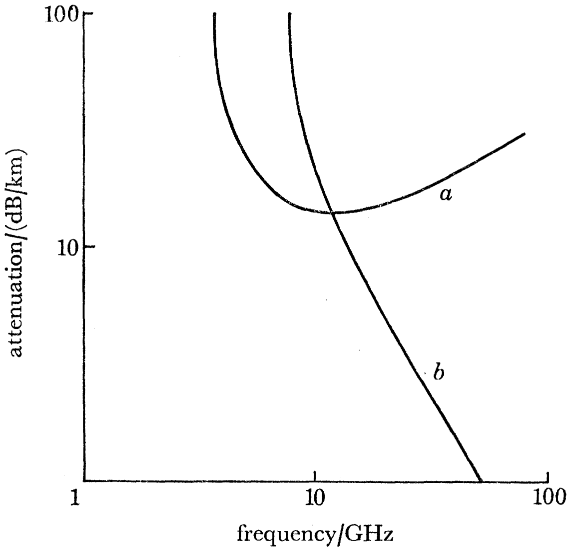


FIGURE 2. Attenuation due to wall loss for 50 mm diameter copper tube: *a*, $TE_{11}$ mode; *b*, $TE_{01}$ mode.

In trunk waveguide systems employing the $TE_{01}$ mode for transmission, the generation of spurious modes is highly undesirable for two reasons:

(i) Other modes suffer high attenuation so that energy extracted from the $TE_{01}$ mode is dissipated and the overall system transmission loss is increased.

(ii) In general, different modes have different transmission velocities. This means that energy coupled from the $TE_{01}$ mode into another mode and then back to the $TE_{01}$ mode some distance later will have suffered a change in transmission time relative to energy which has not been subjected to mode conversion; signal distortion results. Higher order low-loss modes, $TE_{0n}$ modes, are particularly troublesome in this respect.

## 3. Practical $TE_{01}$ waveguide transmission systems

If two parallel waveguides are continuously coupled together, for example by coupling holes in a common side wall, then energy is passed from one waveguide to the other and back again cyclically along the guides. The waveguides might be propagating different modes, but if the phase-change coefficient is the same in each waveguide, the degenerate case, then there will be complete transfers of energy from one waveguide to the other. If the phase-change coefficients are different, the non-degenerate case, and the coupling is sufficiently small, then there will only be transfers between the waveguides of part of the energy in the main waveguide (Karbowiak 1959). A similar situation can exist in a single waveguide in which there is coupling between modes. For circular waveguides, the $TE_{01}$ and $TM_{11}$ modes have the same phase-change coefficients and this degeneracy must be removed if energy is not to be transferred back and forth to the $TM_{11}$ mode with consequential high transmission loss. Lining the tubular waveguide with a dielectric film, for example 0.2 mm of polyethylene, is a technique for separating the phase-change coefficients; the $TE_{01}$ mode has no electric field at the waveguide wall and so the dielectric film has no effect on the phase-change coefficient, but the $TM_{11}$ mode with an electric field at and normal to the waveguide wall (figure 3) suffers an increase in the phase-change coefficient, so removing the degeneracy and enabling the $TE_{01}$ waves to travel around low-curvature bends without excessive loss (Karbowiak 1956). An alternative approach is to use a waveguide with a continuous built-in filter for absorbing energy from any spurious modes produced in the transmission system; the helical waveguide is of this type (Miller 1954).

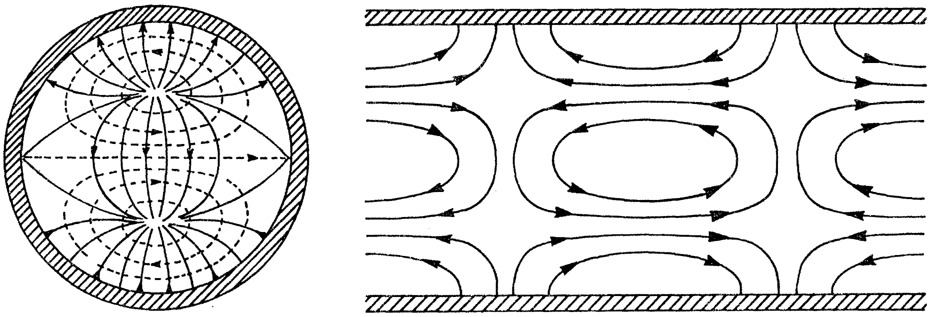

FIGURE 3. Electric field configuration for $TM_{11}$ mode in round waveguide.

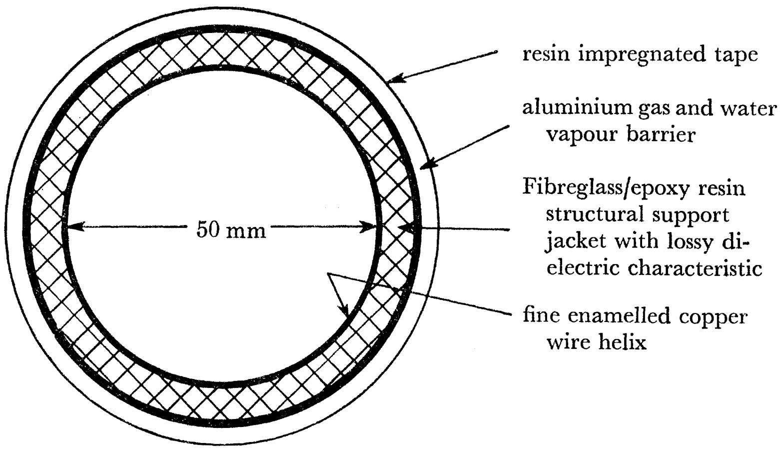


FIGURE 4. Cross section of helix waveguide (not to scale).

It was seen in the previous section that only circumferential wall currents are associated with the $TE_{01}$ mode; the waveguide can therefore consist of a series of closely spaced insulated conducting rings. A waveguide so constructed will not support longitudinal currents; energy from modes associated with such currents is radiated from the gaps between the rings and can be absorbed by a lossy jacket thereby overcoming the mode conversion/re-conversion problem. A tightly wound helix of fine enamelled wire (0.122 mm diameter) is a satisfactory alternative to closely spaced conducting rings, and this type of waveguide can be produced readily in a factory. Figure 4 shows the cross section of waveguide currently being used by the Post Office. The helix is wound in 3 m lengths on precision stainless steel mandrels 50 mm in diameter, the jackets built up as indicated and the epoxy resin cured, after which the mandrels are withdrawn. The waveguide is jointed into 9 m lengths for delivery on site.

For a field trial, 14.2 km of waveguide were laid between the P.O. Research Centre at Martlesham Heath and Wickham Market; the route chosen involved taking the waveguide alongside carriageways, across country, over a stream and through a marsh, and was representative of routes which could be encountered elsewhere in the U.K. The waveguide was drawn into a 100 mm diameter steel duct laid at a depth of 1.2 m; the duct provides mechanical protection, decouples the waveguide from small scale variations in earth conditions and, because the overall waveguide diameter is smaller than the duct diameter, the waveguide assumes a curvature smoother than that of the duct. The waveguide is tensioned to ensure


FIGURE 5. Overall attenuation of 14.1 km field trial route including three sharp 90° bends.

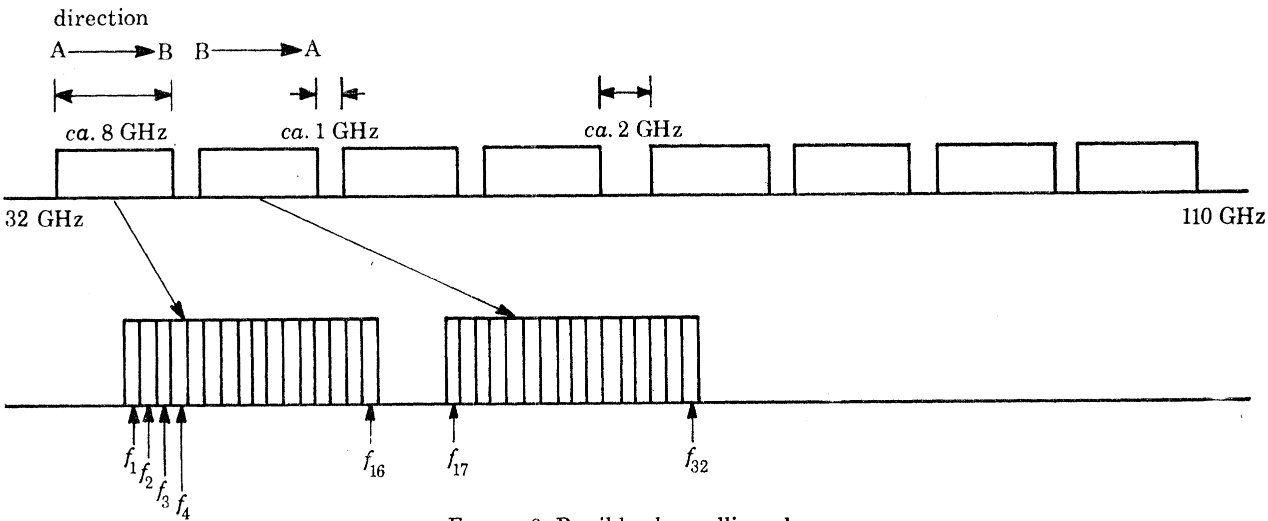


FIGURE 6. Possible channelling plan.

maximum straightness and to overcome changes in length due to temperature variations. The route was selected so that the waveguide was as straight as possible with the radius of curvature almost always greater than 300 m and never less than 100 m thus minimizing losses due to mode conversion. Excessive curvature was unavoidable in three places and specially designed 90° bends, radius about 1.5 m, in 18 mm diameter dielectric lined waveguide were inserted between waveguide tapers; the loss penalty was about 0.25 dB per bend.

The waveguide is filled with oxygen-free nitrogen at about 70 kPa thus excluding water vapour and oxygen which would cause prohibitive transmission losses due to absorption, particularly at the 60 GHz oxygen absorption band. The duct is pressurized with dry air at about 35 kPa to ensure that moisture is excluded from the system.

The measured overall transmission loss is given in figure 5 and compares well with the predicted loss taking into account $TE_{01}$ attenuation, and mode conversion calculated from mechanical measurements of the waveguide and the effects of slow and sharp bends.

## 4. Channelling arrangements

The enormous bandwidth capability of waveguide systems will ultimately be utilized by transmitting up to 64 carriers in each direction of transmission, each carrier being modulated at around 560 Mbit/s necessitating channel spacings of about 560 MHz. A possible channelling plan is indicated in figure 6. Initially a waveguide system would be equipped to transmit a limited number of carriers, as dictated by traffic requirements, and it would be sensible to use the lower frequencies first because at the higher frequencies microwave components will have to be made to greater accuracy and will be correspondingly more expensive.

Other channelling arrangements might be desirable. Thus the band 30–70 GHz could be used for one direction of transmission and the band 70–110 GHz for the other, and during the growth period some of the carriers could be modulated at 280 Mbit/s so that cheaper modulating and demodulating equipments could be used.

## 5. Field trial channelling equipment

Band-branching networks are used to separate the blocks of carriers lying within the frequency bands: 32–40 GHz; 41–49 GHz; 52–68 GHz; 72–88 GHz; and 92–110 GHz.

The branching technique used (Watson 1973) is best illustrated by explaining how received carriers in the 32–40 GHz band are extracted at a repeater. Referring to figure 7, the 50 mm diameter waveguide is tapered down to 15 mm diameter waveguide which can then be split into two semicircular waveguides without distorting the field pattern. The semicircular waveguides are then separated to incorporate a dominant mode rectangular waveguide into which the magnetic field can couple through a series of small holes in the extremely thin waveguide wall. An inspection of the magnetic field pattern (*a*) shows that for the forward wave no coupling exists for any frequency band. The second pair of semicircular waveguide tapers, however, have a $TE_{01}$ mode cut-off frequency of 40 GHz and are slightly different in design so that the reflected 32–40 GHz carriers are in anti-phase at the coupling holes, magnetic field pattern (*b*), and all of their energy is coupled into the rectangular waveguide from which it passes to the next stage of channelling equipment. The same technique is used for extracting from and inserting into the main waveguide blocks of carriers lying in the other frequency bands.

The individual carriers are extracted from the broad band blocks by using a simple interference-type filter system constructed in rectangular waveguide (Bodonyi 1973). Figure 8*a* shows two 3 dB directional couplers connected by waveguides of differing lengths. When the phase changes which occur in the directional couplers are taken into account, it readily follows that if

$$D-d = \tfrac{1}{2}(2n-1)\lambda_g,$$

then there will be an output at port 3, and if

$$D-d = n\lambda_g,$$

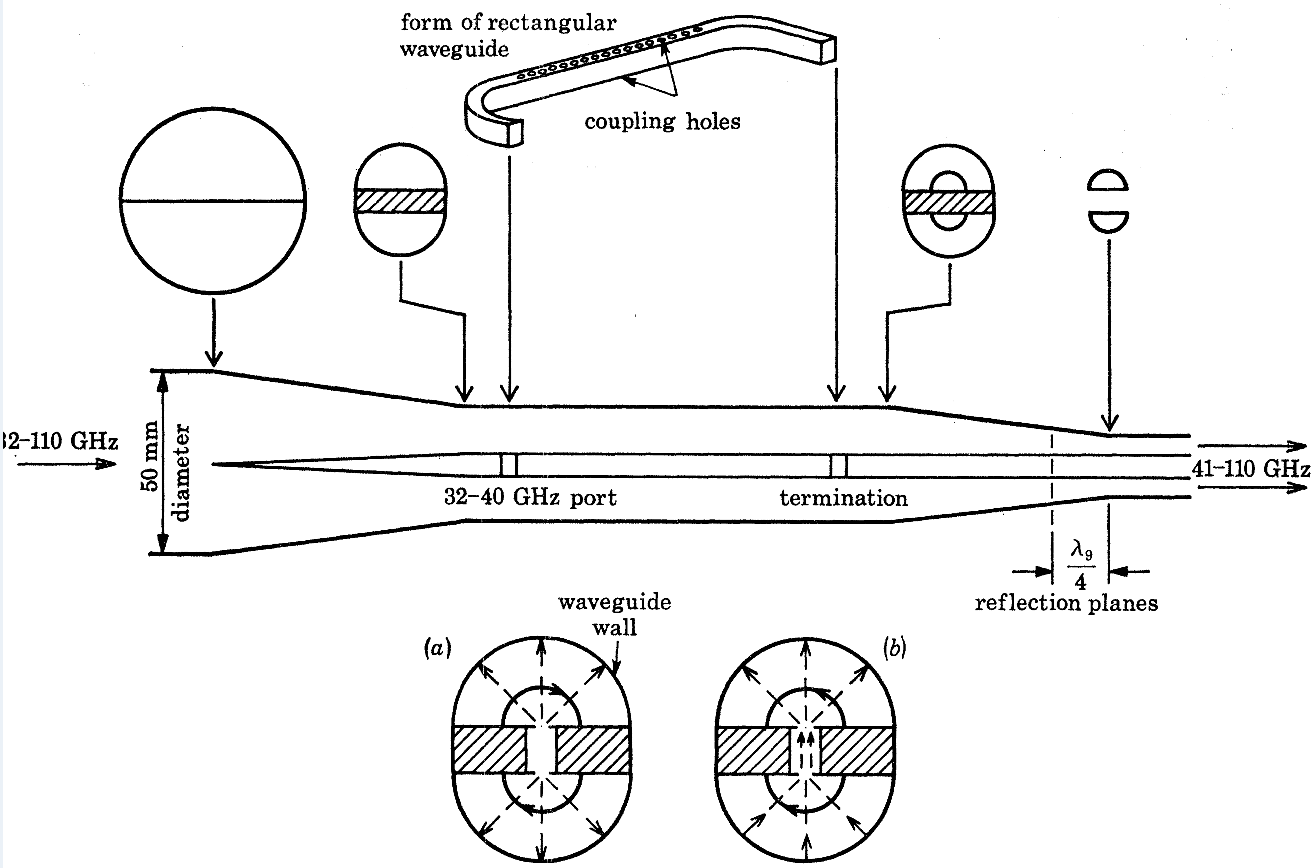


FIGURE 7. Band-branching unit: (*a*) forward wave not coupled into rectangular waveguide; (*b*) reflected wave coupled into rectangular waveguide. Not to scale.

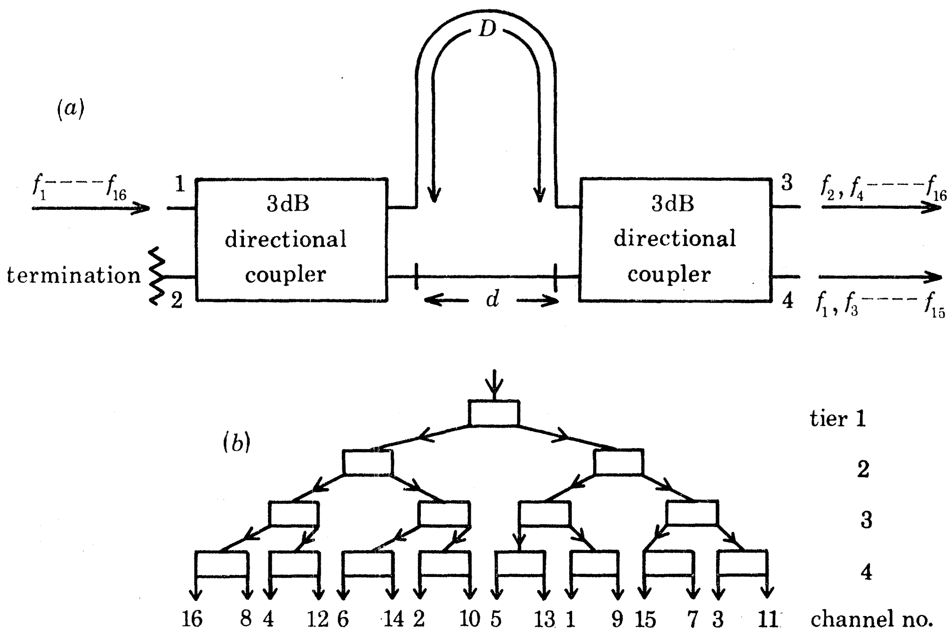


FIGURE 8. (*a*) Interference-type filter; (*b*) assembly of filters.

then there will be an output at port 4 ($\lambda_g$ = guide wavelength, $n$ is an integer). By a suitable choice of $D$ and $d$, and the use of four tiers of filters as shown in figure 8*b* the sixteen carriers of a block can be extracted from or inserted into the system. The overall transmission characteristic of a channel is given in figure 9. The channelling equipment described was developed by the Marconi Company Limited under a Post Office R. and D. contract.

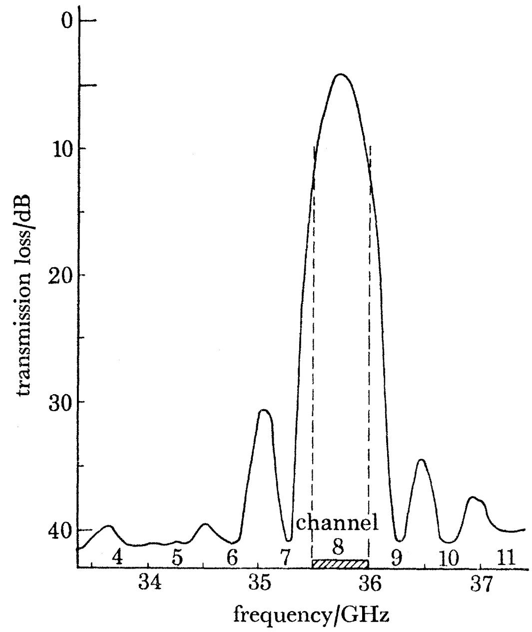


FIGURE 9. Overall transmission characteristic of channel 8.

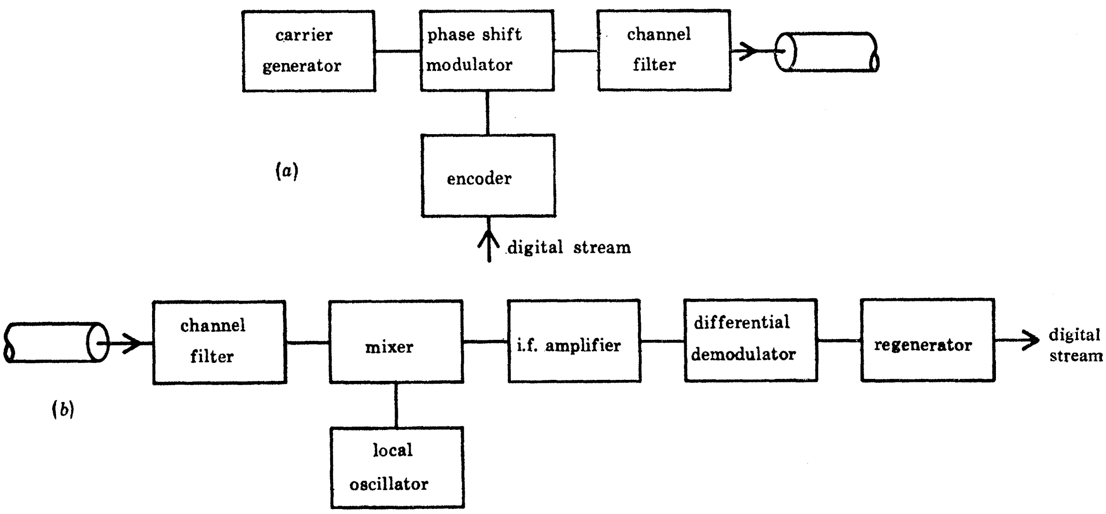


FIGURE 10. Terminal/repeater channel equipment: (*a*) transmitter; (*b*) receiver.

## 6. Basic digital transmission equipment

The U.K. Post Office is now planning a trunk network which will employ digital transmission and be suitable for all types of service; waveguide systems, with their enormous bandwidth transmission capability, will be especially suitable for carrying traffic over the heavily loaded routes in this network.

A waveguide system will transmit a large number of 140 Mbit/s digital streams but, to use equipment efficiently, pairs of 140 Mbit/s streams will be combined (multiplexed) to form 280 Mbit/s streams and each carrier will be modulated by one or two of these 280 Mbit/s streams.

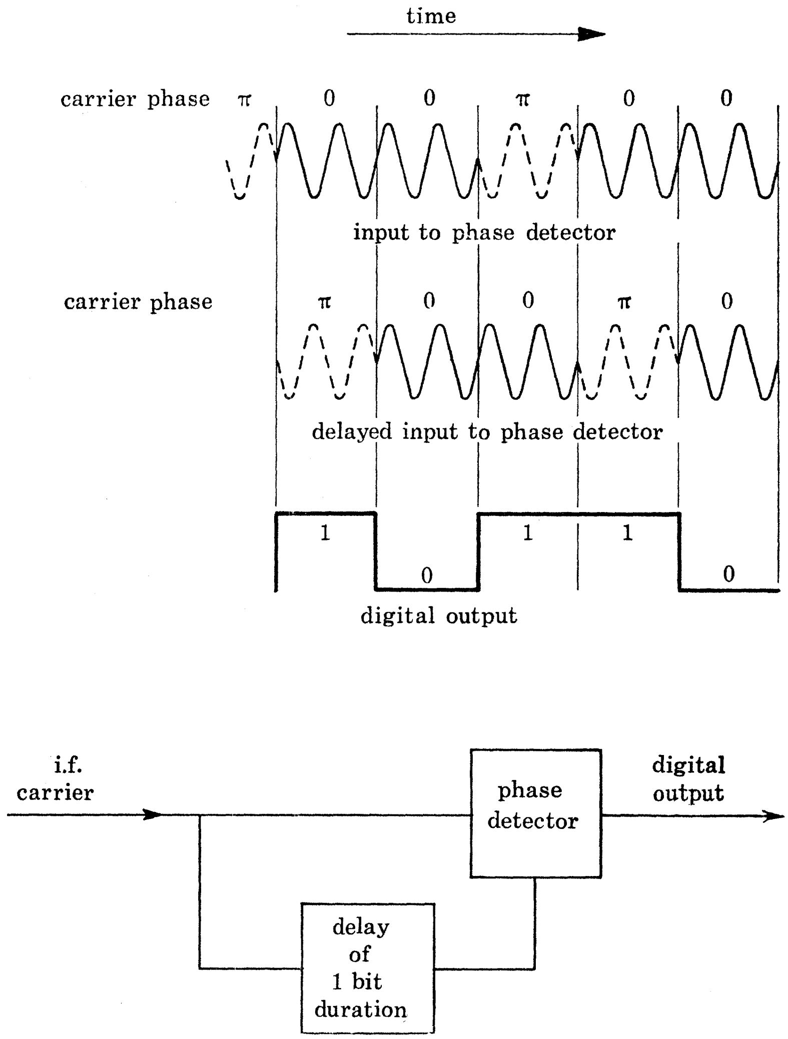


FIGURE 11. Differential demodulation.

At a terminal or repeater, a channel transmitter in its simplest form consists of a c.w. source at the transmit frequency, the phase of which is adjusted by a modulator in sympathy with the incoming digital stream (figure 10*a*). This is known as phase shift keying; in the binary phase shift keyed system, the phase of the carrier is in one position for the transmission of a 0 and is changed by 180° for the transmission of a 1. A channel receiver (figure 10*b*) is of the super-heterodyne type. The incoming signal is heterodyned with a local oscillator signal in a mixer to provide an intermediate frequency of, say, 1.25 GHz which is amplified and provides the receiver gain. The amplified i.f. signal is then passed to the demodulator which extracts the digital signals after which they are regenerated, that is distortion is removed. Figure 11 shows a very rugged form of demodulator in which the phase of the carrier is compared with that for the preceding bit, a phase change of $\pi$ radians indicating that the digit is a binary 1, otherwise it is a binary 0; this is known as a differential demodulator. It is necessary when using this type of demodulator to encode suitably the bit stream before it is passed to the transmitter.

Multiphase keyed systems can be used which have greater digital capacity within a given bandwidth but at the expense of increased transmitter power and sensitivity to interference from neighbouring channels. Thus in a quaternary phase shift keyed system two carriers in quadrature are each binary phase modulated and combined so that, depending on the incoming bits, the resultant carrier phasor is placed in one of four positions.

The explanation of why, for example, a quaternary phase shift keyed system has the same spectrum width as either of the two binary phase shift keyed components is as follows. If, for simplicity, it is assumed the two independent digital streams are repetitive and of the same period, then the frequency components of each modulated carrier will be the same but the amplitudes and phases will be different. Clearly at any given frequency the two components can be combined to produce another component at the same frequency but of differing amplitude and phase. Hence the overall spectrum width will be the same.

When a waveguide system goes into service and is lightly loaded it would be reasonable to employ binary phase shift keying; conversion to quaternary phase shift keying, with its more complex equipment, would take place as the traffic loading increased.

Table 1

| channel no. | 1 | 16 | 32 |
|---|---|---|---|
| centre frequency/GHz | 32.25 | 39.75 | 48.75 |
| channel mid-band filter loss/dB | 4.8 | 4.9 | 6.2 |
| route loss/dB | 42 | 32 | 26 |
| signal-to-noise ratio for an error probability of $10^{-9}$/dB | 23 | 24 | 21.5 |
| system margin/dB | 13.5 | 17.5 | 23.6 |

## 7. Martlesham Heath–Wickham Market field experiments

The terminals at Martlesham Heath and Wickham Market of the 14.2 km waveguide route are equipped for working four channels in each direction. Seven of the channel frequencies lie between 32 and 49 GHz, and the eighth channel with centre frequency 70 GHz was equipped to demonstrate the practicability of using the very high frequency channels.

The performance of each channel was measured by applying independent pseudo-random test sequences at 250 Mbit/s to the two inputs of the quaternary-phase encoder at the transmitter and inserting attenuation in the circular waveguide until an error probability of $10^{-9}$ was achieved at the receiver regenerator output; the inserted attenuation gave the system margin for the channel under test. The signal power-to-noise power ratio was determined at the demodulator input under the above conditions. The measured performance of three of the channels is given in table 1. The lowest system margin for the eight channels was that for channel 1, namely 13.5 dB. For this channel the margin corresponds to the attenuation of 4.5 km of waveguide; the system performance would therefore be maintained with a repeater spacing of 18.7 km, and the error probability would be well below the value of $10^{-10}$/km likely to be recommended internationally for digital systems.

Digital colour television transmission has been successfully demonstrated over four channels connected in tandem, corresponding to a route length of 57 km.

Now that the field trial has demonstrated the practicability of long distance waveguide transmission, the Post Office has decided to install an operational waveguide system between Reading and Bristol, a distance of 125 km. Detailed discussions are now in progress with the manufacturers and full details, with time scales, will be made known soon.

## .8. Review of waveguide system development

It is of interest to review the stages in the development of waveguide transmission systems. As has been stated, the basic theory for the propagation of electromagnetic waves in hollow tubes was available by the end of the nineteenth century, and although Southworth in 1936 appreciated the potential of the $TE_{01}$ mode for long distance waveguide transmission systems it was not until 1947 that Barlow published detailed system proposals. Underground plant is suitable for telephone cables up to about 50 mm diameter, and waveguide of this size only could seriously be considered. Signal sources and components for upwards of 30 GHz were therefore required for experimental work, and as these became available from the mid-1950s onwards rapid progress was made, a milestone being the I.E.E. Convention on long-distance transmission by waveguide in 1959. Thereafter interest in most countries seems to have waned; this was probably because such high-capacity systems, which to be economic had to be fairly heavily loaded initially, were unattractive to network planners and also the appreciation that the only signal sources available, high voltage klystrons, were not reliable enough for operational systems. The advent of low-voltage solid-state signal sources capable of working up to frequencies in excess of 100 GHz, the forecast growth of wide-band services, and the long term planning of national digital networks gave a renewed impetus in the mid-1960s to waveguide system development which has continued in the major countries until today.

It is impossible to highlight many research contributions which, by themselves, have resulted in significant advances in the art; reference must, however, be made to the early work on waveguides by Southworth (1936) and Schelkunoff, and, in particular, Albersheim's contributions on coupled transmission lines and $TE_{01}$ mode propagation in curved waveguide (1949). That long-distance waveguide systems are now viable is due, mainly, to scientists and development engineers of many countries who have resolutely tackled and solved the relevant problems during the last twenty years.

Acknowledgement is made to the Director of Research of the Post Office for permission to publish this paper.

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## *Discussion*

P. A. Lindsay (*Department of Electronic and Electrical Engineering, King's College, Strand, London WC2R 2LS*). One of the most fascinating questions, of considerable financial importance, is whether the millimetre-wave systems will have a chance to be fully developed, or whether they will be superseded by optical systems. I wonder if Mr Davidson would care to comment on this delicate question?

C. F. Davidson. There are four techniques available for 'guided' transmission systems in the 1980s, namely balanced pair and coaxial cables, waveguide and optical fibres. The relative merits depend very much on the distance to be covered and the rate of traffic growth, and there is as yet no clear indication that any one technique will be superseded for all applications during this period.

In the case of the Reading–Bristol route, additional capacity is required to meet the high traffic growth predicted for the early 1980s. The Network Planning Department of the Post Office compared the economic and operational factors of a waveguide system with mixed coaxial and optical fibre cable systems for the route, and concluded that a waveguide system was viable. The technology for waveguide systems now exists and little additional system development needs to be carried out; an operational waveguide system can therefore be available by the date required.

Fibre-optic systems have been demonstrated, and development is expected to proceed rapidly so that operational systems are likely to become available within a decade. Cost estimates show that fibre-optic systems might well prove to be more economic than coaxial cable and waveguide systems for nearly all applications in the longer term.



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