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Communication by Laser

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Synopsis: After a discussion of the possibilities of transmitting optical frequencies through the atmosphere for communication purposes, the various methods of realizing guided transmission systems are reviewed. Attention is paid to systems composed of glass lenses, guiding systems consisting of optical glass fibers and to devices in which for guiding use is made of the gradient of the thermal index of gases.

Finally the application of lasers is considered as sources in long-distance and short-distance communication links and as sources in communication links between satellites.

1. Introduction

The difficulties with the radiopropagation of the higher frequencies in the atmosphere and the problems of designing practical and economical guiding systems have limited the spectrum of electromagnetic waves commonly used in communications to frequencies below 10 GHz. However the big expansion of conventional microwave systems has begun to saturate the possibilities offered by the frequency bands allocated to radio links in the centimetric wavelength region and will necessitate the use of new parts of the r.f. spectrum for communications in a few years. This has led to a renewed and important effort to use the frequencies above 10 GHz in terrestrial radio links and in satellite communication systems; similarly the millimetric circular waveguide systems are now arriving in a developmental state. The recent progress in integrated circuit techniques and in microwave technology, especially in the field of microwave solid state devices, are important factors in the design and economic evaluation of these new systems compared to more conventional ones.

In the field of the visible and the infrared wavelengths, the discovery of the laser led also to a breakthrough in the technological art and it is interesting to examine whether this can open a new part of the frequency spectrum to communications. It appears that the problem of transmitting light waves over great distances is the key problem at the development of these new possibilities. So, a great part of this article will be devoted to this problem. We shall try then to evaluate in what kind of communication systems lasers could be applied, taking into account the recent progresses in the field of coherent sources and optical components. Let us first examine the two ways of transmitting light waves at a great distance: either in the atmosphere, or by a guided wave system.

2. Transmission through the Atmosphere

Before the discovery of lasers, it has been shown that, beside the window in the visible, there are other windows of transparency in the infrared, separated by strong absorption bands due to the constituents of the atmosphere, mainly water vapor, carbone dioxide and ozone [1]. One of the most interesting windows appears to be that near the wavelength of 10 µm. It permits the propagation of the waves emitted by the carbon dioxide laser: in fact these waves are less affected by the effects of turbulence and by scattering of light in mists and fogs, the two main difficulties encountered in the atmospheric propagation of light.

2.1. *Effects of Turbulence*

Even in clear weather, turbulence induces local inhomogeneities whose dimensions vary from a few millimeters to more than

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ten meters. Their effect on the light beam depends on the diameter d of the beam compared to the mean dimension of the inhomogeneities l. When $\frac{d}{l} < 1$, the beam is deflected as a whole by these inhomogeneities and this leads to a random angular deviation of the beam and a displacement of the light spot at the receiving end. When $\frac{d}{l} > 1$, the main effect is interference between small fractions of the beam which are independently diffracted: this leads to a non-uniform repartition of the light intensity at the receiving end, to wavefront distortion, to spatial coherence degradation and to scintillation [2].

These effects must be taken into account in the design of an optical communication link. Servo-systems may be needed to maintain a continuous link between emitting and receiving points in spite of the slow variations of the beam position and direction due to turbulence and slow variations of the refractive index. More fundamental is the limitation produced by random phase front distortion by turbulence, when an optical heterodyne receiver is used; there is an optimum value, above which an increase of the diameter of the receiving antenna leads to a decrease in signal-to-noise ratio. However, optical links with direct detection are more *generally* considered. So, the more important limitation is scattering by mist and fog.

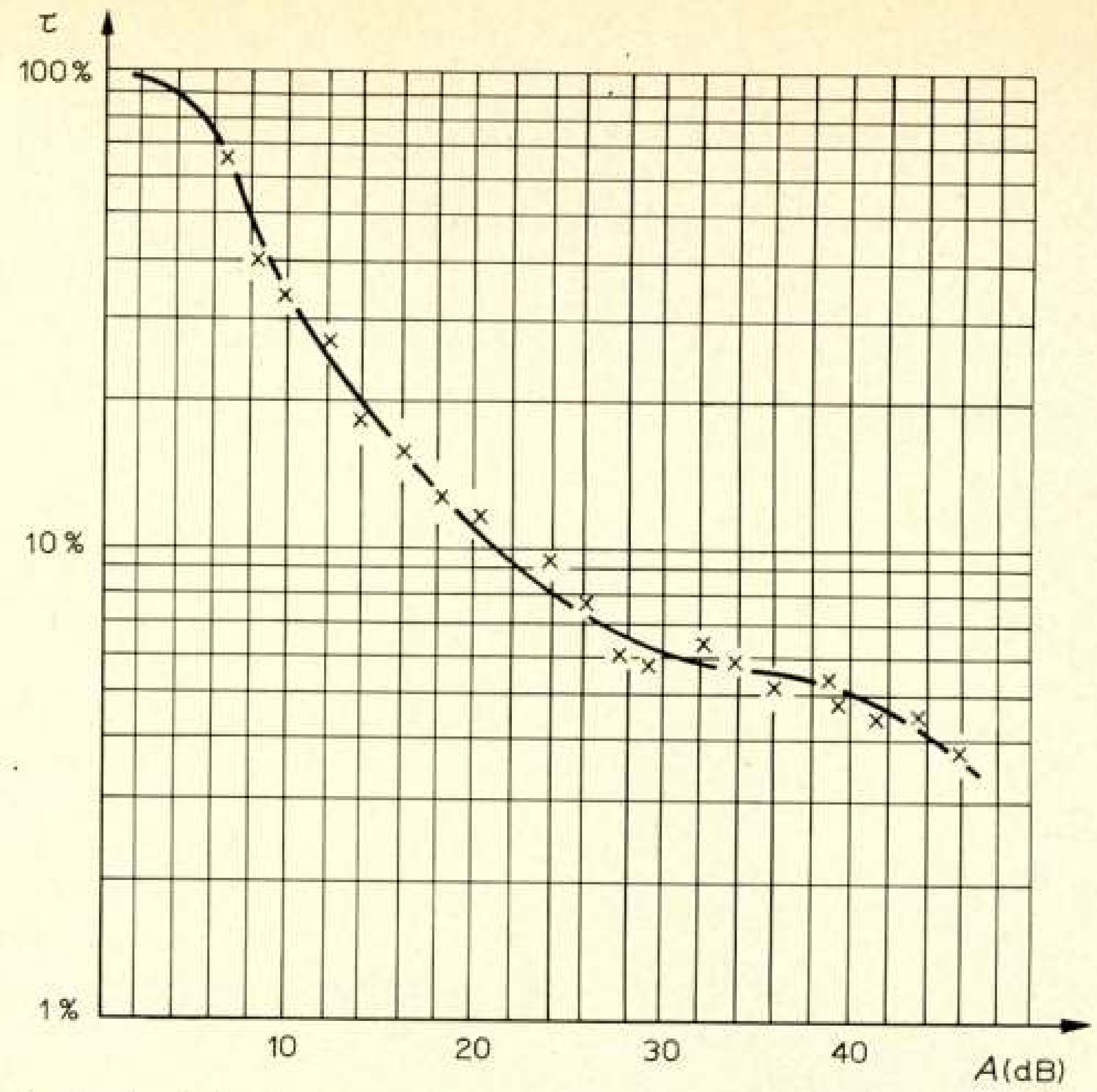


Fig. 1. Statistical propagation results at 0.63 μm, on a 1.5 km path. CNET-Lannion, Brittany (France).

2.2. *Scattering by Mist and Fog*

Scattering by particles which are small compared to the wavelength, is very selective and leads to an attenuation given by the Rayleigh formula:

$$\alpha_s \text{ (dB/km)} = 3.60\, N A^3 \lambda^{-4}$$

with

N = number of scattering centers per cm^3;
A = cross-sectional area in cm^2;
λ = wavelength in cm.

However, when the scattering particles are of the order of magnitude of a wavelength, or larger, the attenuation is much less dependent on the wavelength. Scattering in the atmosphere is produced by aerosols, suspensions of particles of smoke, dust, water drops, etc. We refer here to the simultaneous measurement of particle size distribution and of the transmission through mists and fogs, done by *Arnulf* et al. [3]. In mists, they found that the radius of the water droplets was generally less than 1 μm, with a maximum near 0.5 μm. This is in accordance with the fact that the attenuation of mists depends very selectively on wavelength and is much smaller at 10 μm than in the visible. In fogs, especially in country fogs, the water droplets can have a radius of more than 10 μm, and their attenuation is not very dependent on wavelength. However, urban fogs, consisting of condensation of water around smoke and industrial dusts, can be much more selective. Typical values for industrial smokes are an attenuation of 200 dB/km at 0.55 μm and of only 5 dB/km at 10 μm. In general these fogs are less selective; they can give an attenuation of 150 to 300 dB/km in the visible with approximately half this value at 10 μm.

Statistical results on propagation at 6328 Å, obtained during a period of 8 months, from January to August 1970 on a 1,5 km long path at the CNET Research Center of Lannion (Brittany) are shown on Fig. 1. It can be shown that the attenuation is greater than 40 dB during 5% of the time, i.e. for approximately 18 d/a. Such a result depends greatly on local meteorological conditions and cannot be generalized.

Scattering by mists and fogs limits the possibility of using visible light for establishing continuous, reliable links all the year around. But such optical links can be possible and useful in regions with favourable meteorological conditions or, for temporary links in some special cases. Somewhat different is the case of the 10.6 μm infrared light emitted by the CO_2 laser [4]. The smaller attenuation by dispersive fogs, common in an urban atmosphere, gives some possibilities of using it, for instance in local networks between telephone exchanges.

3. Guided Transmission Systems

For millimeter waves, the limitations of atmospheric propagation lead to try to use guiding systems to transmitting the wave over great distances. The technique of hollow metallic waveguides such as TE_{01} circular waveguides, used in the microwave region, cannot be easily extrapolated in the optical region. So other solutions are in study, gathered either from dielectric waveguide techniques, which lead to different types of optical fibers, or from the optical techniques using a series of lenses and mirrors for guiding a light beam. These two techniques make use either of many media having different refractive index, or of a medium having a continuously varying index: the dielectrics used are either glasses or fused quartz, or a gas in which index changes can be produced by a non-uniform temperature. So, many systems have to be considered, but in each case many conditions have to be fulfilled:

a. The propagation medium must introduce a low attenuation of the beam. A rough estimation shows that the attenuation has to be less than 20 dB/km, but a comparison with millimetric circular waveguides leads rather to a desirable value of 5 dB/km; this condition is easily obtained with gases, but not at the present time with glasses.

b. In straight line sections, the guiding system has only to compensate the beam divergence due to diffraction, which requires only a mean value of refractive index changes of, say, 10^{-6}. Such changes can be easily obtained in gases.

c. The system must guide the beam around curves with the smalles possible radius of curvature. This radius can be made smaller and smaller, when larger refractive index changes can be applied, which gives an advantage to glasses on gases.

d. These three conditions have to be fulfilled by a system which can easily be put into service and which must not be too expensive.

Three families of guiding systems are in study at the present time:
- guidance by a series of glass lenses;
- guidance by optical glass fibers;
- guidance by thermal index gradient in gases.

3.1. *Guidance by a Series of Glass Lenses*

Guidance of a light beam can be obtained by an iterated series of convergent glass lenses having the same focal length F and separated by the same distance D. Such a periodic series is a stable guiding system if $0 < D < 4F$: in that case, a paraxial ray remains at a finite distance from the axis, whatever the number of sections. The middle of the stability domain is given by $D = 2F$, i.e. by confocal lenses and this configuration is generally chosen.

Many laboratories have studied such systems. As an example, we give some details about the system tried out by *Dr. Goubau* [5]. The light guide has a total length of 970 m and is made of ten sections of 97 m, separating fused silica lenses ($F \# 50$ m). The attenuation measured on each antireflection coated lens lies between 0.03 dB and 0.05 dB. The light beam is protected by an aluminium pipe with $\phi = 10$ cm, which can be evacuated. The pipe is not buried in the earth, but is placed approximately 1 m above the ground and is protected from thermal variations only by a small isolating sheath. So, in order to avoid defocusing by temperature changes in the gas remaining in the pipe, the pressure has to be less than 10 mm Hg. In such conditions, the total measured attenuation is as low as 0.5 dB/km.

This system satisfies our first two conditions: it has a low attenuation and it can compensate the diffraction of the light beam in a straight line. But it is not very satisfactory from the point of view of the two other conditions: it is difficult to follow a continuous curve with a small radius of curvature and it is complicated to lay and to align, as compared with cables, or even with circular millimetric waveguide. But, with these limitations, it can be used already.

3.2. *Guiding by Optical Fibers*

Optical fibers have advantages and disadvantages that lens waveguides lack. They can more easily be manufactured and be laid and they can be bent in curves with a radius as small as a few centimeters. But the attenuation is rather high and still prohibitive for uses in long distance links.

The electromagnetic properties of these fibers can be derived from that of the simple dielectric waveguide made of a dielectric cylinder with refractive index n_1, placed in a dielectric medium of lower index n_2. The propagation modes of this guide are more complex than the modes of hollow metallic circular waveguides. Generally they have at the same time one component of electric field and one component of magnetic

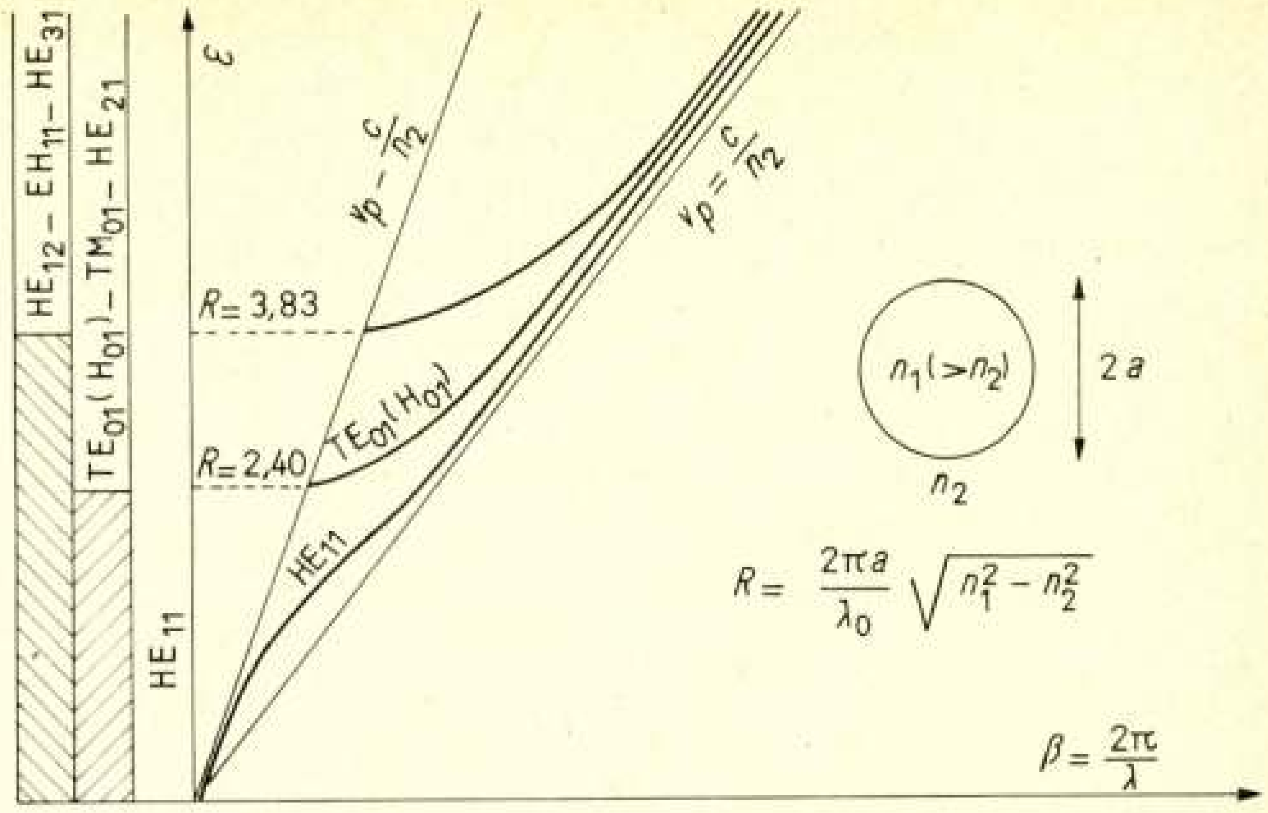


Fig. 2. Dispersion curves of a dielectric waveguide.

field along the direction of propagation. These are denoted by HE_{mn} and EH_{mn}, the first index giving the angular variation of the fields, the second giving the number of zeros along a radius. However the modes with $m = 0$, which have no angular variation of the fields, are purely transverse electric or transverse magnetic and are denoted by TE_{on} (or H_{on}) and TM_{on} (or E_{on}). The dispersion curves (ω, β) of these modes are given in Fig. 2. The phase velocity is equal to $\frac{c}{n_1}$, the light velocity in the internal medium at very high frequency and increases when the frequency decreases. At the cut-off frequency, the phase velocity is not infinite as in metallic waveguides, but becomes equal to $\frac{c}{n_2}$, the velocity in the external medium. The cut-off frequencies are given by definite values of the parameter $R = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$ where a is the radius of the cylinder and λ the wavelength in vacuum. However the HE_{11} mode has no cut-off frequency and exists at all frequencies. Below the lowest cut-off frequency of the other modes only the HE_{11} mode can be propagated, and this gives the possibility of having a monomode waveguide, when the radius of the cylinder is small enough for a given frequency. On the other hand, the greatest part of energy is located inside the internal cylinder, only at high frequencies, i.e. if the radius of the cylinder is not too small. For instance, if $n_1 = 1.45$ and $n_2 = 1$, more than 90% of the energy is located in the inner cylinder if the ratio $\frac{\text{diameter}}{\text{wavelength}} = \frac{2a}{\lambda} > 1$; on the contrary, only 20% of the energy is in this medium when $\frac{2a}{\lambda} < 0.3$ [6]. In the latter case, it is not possible to guide the wave along curves with small radius of curvature. From these conditions concerning $\frac{2a}{\lambda}$ two classes of optical fibers are derived: – monomode fibers and multimode fibers, useful for two types of applications.

Optical fibers are generally made of two coaxial glass cylinders: a core cylinder inside a sheath cylinder, the cladding. In multimode fibers, the diameter of the core is much larger than the wavelength: for instance $2a = 50$ µm, while the diameter of the cladding is of the order of 60 to 100 µm. These fibers have a small information capacity, their frequency bandwidth being limited, for instance, to 20 MHz for 1 km length, by the differences of the propagation velocities of the different modes which can be propagated at the same frequency. The second class of fibers is that of monomode fibers, with a core diameter of the order of the wavelength. As an example $2a = 1$ µm, while the diameter of the cladding will remain 50 to 100 µm for mechanical reasons: their frequency bandwidth can be greater than 1 GHz for lengths of 1 km.

The monomode fibers are much more difficult to manufacture than multimode fibers, whose fabrication is very cheap and straightforward. However the attenuation of these two classes of fibers remains at the present time the main difficulty. The more common values quoted in the literature vary from 300 to 1000 dB/km. A great dispersion in experimental values is a result not only of the great variety in chemical composition of the fibers, but also of the fact that the measurements have been made on short samples. In fact, it appears that there are not enough data on the values of attenuation of different glasses at different wavelengths, and on the origin of this attenuation even in the volume of the glass. Many laboratories have begun to work on this important subject. A first source of attenuation is given by the scattering of light by index inhomogeneities in the medium. Measurements on the angular distribution of scattered light show that the diameter of the scattering centers is generally smaller than the wavelength, but can approach one wavelength in the visible. When the scattering centers have dimensions much smaller than 1 µm, the Rayleigh formula in λ^{-4} gives an important advantage to infrared light: a glass having a scattering loss of 64 dB/km at $\lambda = 0.5$ µm has only a scattering loss of 4 dB/km at $\lambda = 1$ µm. Recent measurements on different glasses at 0.9 µm, the wavelength of the gallium arsenide semiconductor laser, give values of scattering losses of 0.5 to 7 dB/km [7]. Another source of attenuation is the absorption of light by ions such as Co^{++}, Cu^{++}, Ni^{+++}, Fe^{++}, which can give strong absorption bands, even at very small concentrations, of the order of 10^{-6} to 10^{-9}. The effects of these ions vary with the chemical composition of glasses. Generally they are of the same order of magnitude as scattering losses in the visible, and are the more important source of attenuation in the near infrared. Actually, the bulk attenuation of the best-known glasses lies between 50 dB/km and 100 dB/km. This is *not* a physical limit, since attenuation of less than 10 dB/km has been measured on fused silica [8], but this material is not very convenient for the manufacture of optical fibers, due to its low refractive index and to its small thermal expansion, which make difficult to match it with any other cladding material. We can hope that new preparation techniques can reduce attenuation due to absorption by ions. In fact, a very small quantity of glass is needed to make the core: the volume of a cylinder of 1 µm diameter and 1 km length is less than 1 mm³ and it can be possible to reduce the bulk attenuation of such a small quantity of glass, if we can attain the degree of purity which is now common in semiconductor materials.

In any case, the attenuation of between a few hundred and 1000 dB/km, measured at present on the best fibers of one of these types, is much larger than the bulk attenuation of the glass.[1]) Scattering losses in a fiber are particularly large: manufacturing processes create new defects and inhomogeneities, especially at the boundary between core and cladding. While this is not agreed by all, it can be interesting to suppress this discontinuity and to obtain the confinement and guiding of the light beam by a continuously-varying refraction index. Guiding of electromagnetic waves by an index gradient is well-known, and gives rise to familiar phenomena such as mirage. The study of general guiding media, which led to important studies in the recent years [9, 10] has shown the importance of a parabolic distribution law of the refractive index, like $n = n_0 \left[1 - \Delta\left(\frac{r}{r_0}\right)^2\right]$. Although propagation modes can be defined for the continuously-varying index case, it is more interesting to describe the propagation phenomena in terms of light rays, specially if the index gradient is small: for an arbitrary injection angle, the beam follows a sinusoidal or helicoidal path around the axis. Theoretically many light beams can be injected without interference, and this can be used to increase the capacity of small sections of a fibre. But, for long sections, defects and bending of the axis lead to a mixing of these beams.

A parabolic distribution law of the refraction index can be approximately obtained by thermal diffusion and exchange of ions in a glass cylinder: in certain types of glasses substitution of ions like Li^+, Na^+, K^+, Tl^+, Mg^{++}, Ca^{++}, Pb^{++}, could give index variations of 0.01 to 0.03 if it were possible to have a complete substitution; the experimental values obtained are of the order of one fifth of these values [11]. This technique is used in SELFOC [11] and GRIN [12] fibers. On SELFOC fiber samples, an attenuation of between 80 and 250 dB/km has been measured, scattering losses being reduced to 20 or 30 dB/km.

3.3. *Guiding by a Thermal Gradient in a Gas*

Since 1964 many devices have been described in which use is made of the index gradient produced by a thermal gradient in a gas for making lenses or light waveguides [13]. The variations of refraction index in gases are much smaller than in solids. For instance, the air index in normal conditions of temperature and pressure is such that $n - 1 = 3.10^{-4}$, compared to the index of glasses being of the order of $n = 1.5$. For a small variation of temperature ΔT, the variation of the air refraction index is $\Delta n = -10^{-6} \Delta T$. This small variation is sufficient to compensate the effect of diffraction in straight lines. It can be shown that an index variation of $\frac{\lambda^2}{16a^2}$ (λ = wavelength; a = beam radius) is sufficient, which gives a value of 10^{-6} for $\lambda = 1$ µm and $a = 0.25$ mm. But such a variation is not large enough to follow curves with a small radius of curvature, as for instance less than one hundred meters. Among the systems using thermal gradient in gases, those which have a continuous structure, rather than discrete lenses, seem particularly practical to realize a transmission line. A parabolic index distribution, is of interest like in glass fibers, such that

$$n - 1 = -10^{-6} \Delta T \frac{x^2 + y^2}{b^2}$$

(Ox, Oy are the axes in the transverse section; b is a parameter characterizing the distribution). However, it is difficult to obtain this distribution in a gas. It can be realized approximately

[1]) Less than one month after the MOGA Conference, an important experimental result on two-glass optical fibers has been announced by *F. P. Kapron* et al. at the conference on 'Trunk Telecommunication by guided waves' (London, 29 September-2 October 1970). We quote: '*two 30-meter sections which were investigated had a total loss of between 60 and 70 dB/km; the lowest value of total attenuation observed in all waveguides constructed for this work was approximately 20 dB/km, measured at a 632.8 mm wavelength*' [24].

by injecting a laminar flow of fresh air in a hot tube. But when the gas becomes homogeneously heated, the lens effect fades away and it is necessary to inject new fresh air in the tube. Such a system is made of a succession of sections where fresh air is injected at one end, while warm air can escape at the other end [14]. Another difficulty arises from the convection motion: fresh air at the center of the tube begins to fall while heated air climbs along the wall of the tube.

We shall now describe an helicoidal structure which can suppress this convection motion [15]. In the helicoidal light guide, the index gradient in the gas is obtained by a quadrupolar structure, made for instance by four tubes, the circular sections of which are placed at the corners of a square (see Fig. 3). Two tubes at opposite corners are at the temperature $T_0 + \Delta T$; the two other tubes are at $T_0 - \Delta T$. These tubes are twisted around the axis determined by the centre of the successive squares. The index distribution in the transverse section is given by:

$$n = 1 - 10^{-6}\,\Delta T\,\frac{x^2 - y^2}{b^2}$$

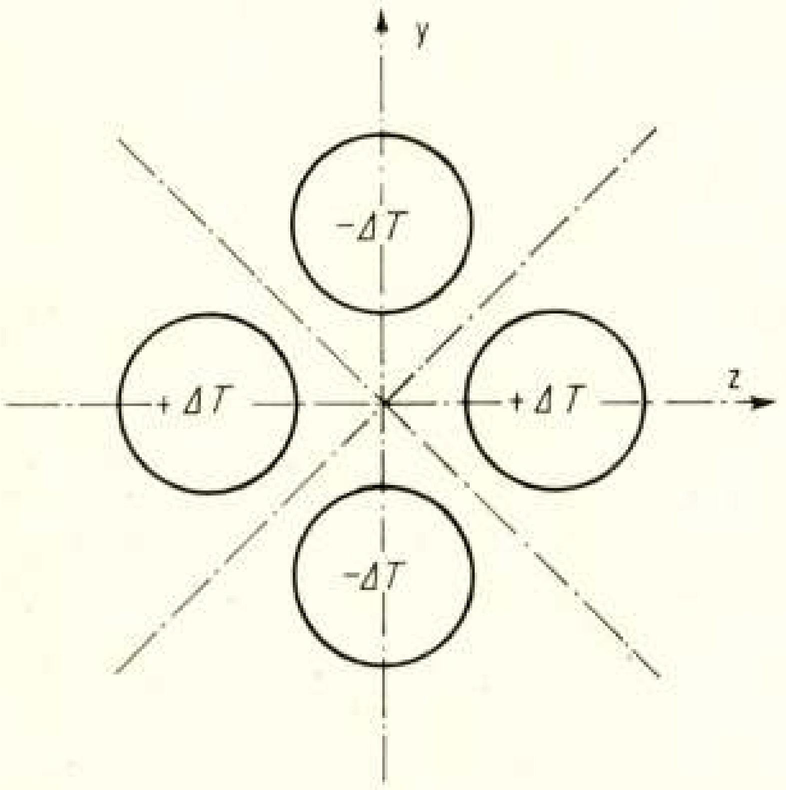


Fig. 3. Section of the helicoidal waveguide.

This gives a converging effect in the plane $x - Oz$, and a diverging effect in the plane $y - Oz$. Due to the helicoidal structure, convergence is obtained alternatively in the two planes: so, this guide is a periodic focusing system, as those used in electron optics, in microwave tubes or particle accelerators. The main properties of this structure have been calculated and they have been verified on an experimental 15 m long assembly. This experiment is very far from the development of a practical and economical waveguide. However, notwithstanding many disadvantages, – difficulty of following curves with a small radius of curvature, problems in manufacturing, laying and operating the guide, – this solution has the advantage of a very small attenuation, much smaller than attained in the present optical fibers.

4. Some Possibilities of Application of Lasers to Communications

Although capital problems remain to be solved in the field of light transmission, it is interesting to consider some systems which can be developed in the future. We shall examine three types of communication links:

- long distance high capacity terrestrial trunks;
- short distance, medium or low capacity terrestrial links;
- communication links between satellites.

4.1. *High-capacity Terrestrial Trunks*

To define what can be a long distance high-capacity trunk in the future, we can remark that in 1970 the largest interurban link in France has 6 600 telephone channels. On a basis of a capacity doubling every five years, the main cities of Western Europe will be connected by 30 000 to 40 000 telephone channel links at about 1985. On the other hand, this capacity needs to be doubled if the number of picturephone channels becomes $^1/_{100}$ of that of the telephone channels. Such a capacity can be obtained with a millimetric circular waveguide using the frequency band between 32 and 40 GHz. In this band, the circular waveguide, which is now arriving at the development state, has a theoretical attenuation of 3 dB/km; the experimental value is 5 to 7 dB/km. With the present technique, the spacing between repeaters can be larger than 10 km and curves can be followed with a radius of 20 m, and even of 10 m. What can the laser offer in this field?

First of all, it must be said that laser systems are not in the same state of development. However, it seems necessary to use

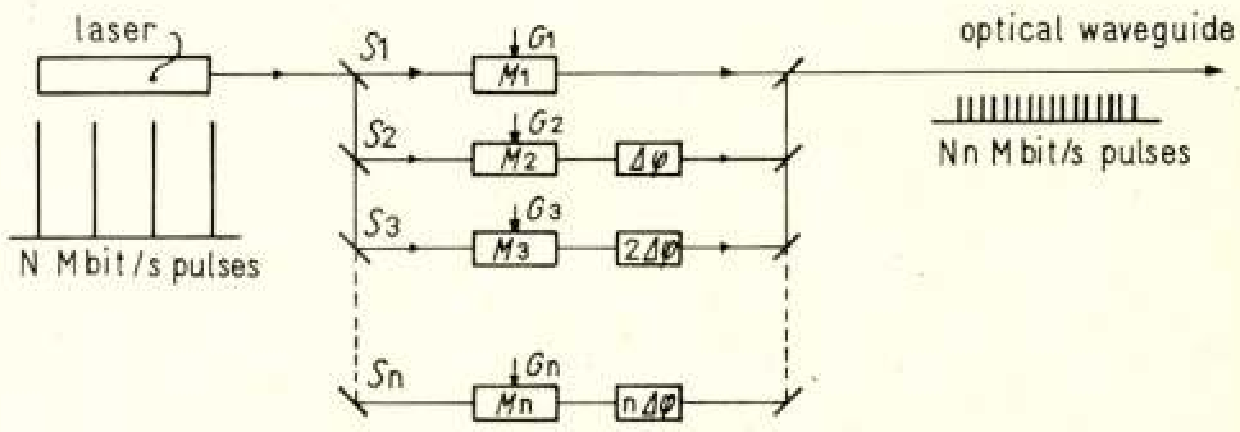
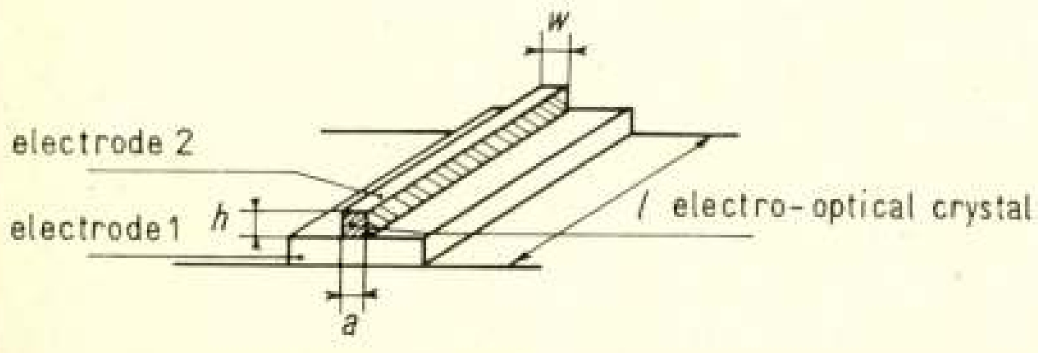


Fig. 4. Optical multiplexing of n PCM signals at N Mbt/s.
M = Modulator; G = PCM signal generator for N Mbit/s; $\Delta\varphi$ = Phase shifter; S = Beam splitter.

a non-dispersive guiding system: a monomode optical fiber would be the ideal guide, if it were possible to manufacture long samples with a total attenuation less than 10 or 20 dB/km. Guiding by a thermal gradient in a gas would be better from the point of view of attenuation, but it still remains to devise a practical and economical gas light waveguide. If none of these solutions still remains will succeed, then already the lens waveguide can be used, but aligning seems to be more complicated and perhaps more expensive than a millimetric circular waveguide. Nevertheless, it can be useful for realizing long sections of very high capacity trunks without repeaters: we can have in mind sections of 20 to 50 km, although it is yet too early to make an economic evaluation of such systems.

In the field of laser equipments, the recent progresses of coherent sources and associated components make such high capacities possible. Among the most promising sources, we must consider the YAG laser (Yttrium-Aluminium Garnet) doped with neodymium, emitting at 1.06 μm. With mode-locking by an internal modulator, it can produce short recurrent light pulses not longer than 30 m, with a peak power of 100 W. Such a laser can be used as an emitter in a pulse-code modulation system. A pulse repetition rate of 250 MHz would give a capacity of 3 000 telephone channels approximately. But the pulses would be short enough to permit time-multiplexing of many such groups of channels: an optical-multiplexing could be used as presented in Fig. 4 [16]. Time-multiplexing of 10 groups gives a capacity of 30 000 telephone channels. But this is not the physical limitation, which is given by the pulse length that is related to the bandwidth of the emitting material. With 30-ps pulses, produced by a YAG laser, a capacity of 10 000 Mbits can be obtained, which corresponds to 120 000 telephone channels. With optical time multiplexing, each 250 Mbits group is separately modulated. The pulses can be modulated by an electro-optical gate, like the modulator shown in Fig. 5. With the use of new materials such as lithium niobate tantalate, together with a transverse modulating field, – which reduces the modulating voltage necessary to open the gate by a factor $\frac{l}{h}$ in which l stands for the length and h for the height of the crystal, – the gate can be operated with a rather low electrical power. The modulator of Fig. 5, made of $LiTaO_3$ ($l = 22.6$ mm; $h = 0.5$ mm; $F_{max} > 1$ GHz), requires only a peak voltage of 60 V and a modulating power of 10 W. However, the YAG laser and this modulator would be much more expensive than conventional solid-state telephone repeaters. So, their use seems limited to long sections of very high capacity trunks, without intermediate repeaters, this means that a waveguide with low losses must be available.

The use of a YAG laser, which seems the best solution at the present time, can be challenged by the rapid progress of



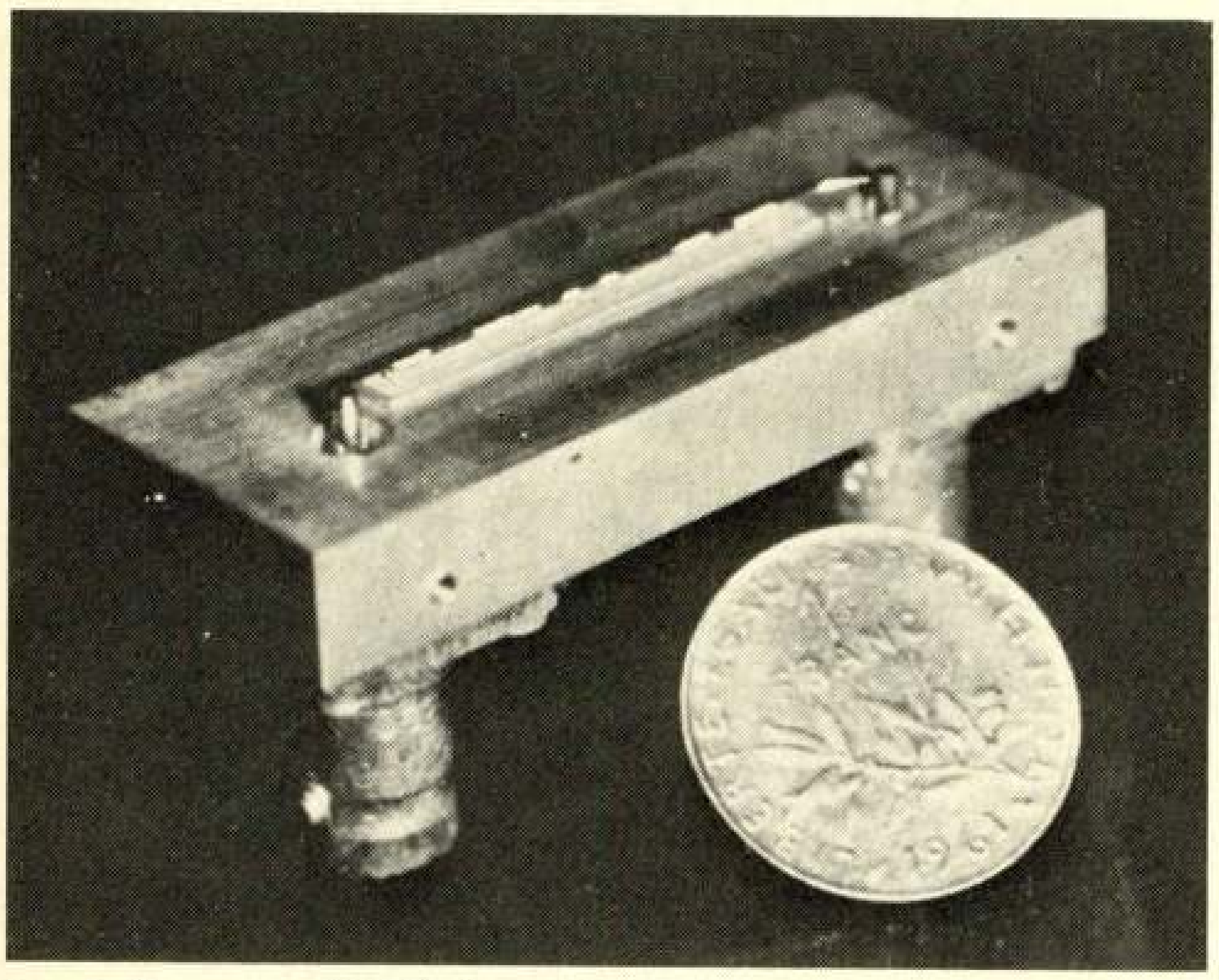


Fig. 5. Transverse field light modulator.

the semiconductor laser, especially the gallium-arsenide laser. The use of this laser has been limited until now because of its high threshold-current which makes c.w. operation at room temperature possible. But the threshold current has been reduced to one tenth in one year. A first step was made in 1969 by *I. Hayashi* et al., at Bell Telephone Laboratories, and by *H. Kressel* and *N. Nelson* at RCA who introduced an heterostructure of As Ga-As$_x$ Al$_{1-x}$Ga [17, 18]. The threshold current of these improved injection lasers was near 8 000 A/cm^2 at room temperature, compared to 26 000 A/cm^2 for the best p-n laser diodes. In 1970, the threshold current has been reduced to 1 000 A/cm^2 in double heterostructure injection lasers [19]. This value is sufficient for c.w. operation at room temperature, at least in a laboratory experiment. Some research work on optical circuits [20] can be used for constructing solid-state communication repeaters. Combined with the use of a monomode optical fiber, whose attenuation could have been reduced to 10 or 20 dB/km, the use of a semiconductor laser and optical integrated circuitry could be a competitive solution to the technical and economic problem of the long-distance high-capacity trunks of the future.

4.2. *Short-Distance, Medium or Small Capacity Links*

There is a need of short-distance communication links, with medium or small capacity, dependent on the applications. The transit centers and big telephone exchanges in large cities are connected by many thousands of telephone circuits, but, for reasons of flexibility, these circuits are generally not multiplexed in a great bandwidth signal. Such needs exist also in suburban areas, with a smaller capacity. Two types of laser communication systems will have to be considered for this application, as well as for similar military applications. One of them would require semiconductor lasers and solid-state optoelectronic devices, with an optical fiber as the transmission medium. Because of the small bandwidth needed, multimode fibers could be used. One interesting feature of such a system would be the low cost of the optical fibers, if we compare the price of glass with the price of copper; however, high-purity glasses would be needed. Another feature is the possibility of putting many fibers in the same bundle, thus making optical telephone cable.

Another way out is trying to use propagation in the atmosphere. In many countries experiments have been done on links with lengths of a few kilometers, using gas lasers, especially helium-neon lasers (6328 Å) and carbon dioxide lasers (10.6 µm). These experiments have shown that applications of optical communication links in the atmosphere are rather limited. However, some non conventional solutions proposed for frequencies above 10 GHz to fight attenuation caused by rainfall can bring some help to fight the attenuation by fogs and mists at optical frequencies [23]. One of these proposals is to reduce the distance between emitter and receiver well within the distance used in conventional line-of-sight distance microwave links. Another one is to connect two points using space diversity by installing several paths of which at each time the path giving the smaller attenuation could be chosen. However, the attenuation due to fogs at optical frequencies is much larger than the attenuation due to rain in the millimetric region. From that point of view, the carbon dioxide laser, emitting in the infrared at 10.6 µm, is more suitable than the helium-neon laser. But this wavelength is much more difficult for modulation and detection; electro-optical modulators need at least ten times more modulating voltage and detectors need to be cooled at liquid nitrogen temperature.

An interesting concept, stemming from the technique at frequencies above 10 GHz, is that of the 'pole-mounted repeaters'. Following the development of microwave solid-state electronics, the volume and power requirements of microwave repeaters have been considerably reduced and for low capacity links the big towers of conventional microwave relays can be replaced by a mast, at the top of which a compact repeater is placed. It seems possible that such solutions can be extrapolated in the optical region if new progresses in semiconductor lasers and optical integrated circuits lead to compact laser repeaters.

These two ways of using lasers in the atmosphere can help the solution of the problem of local networks in urban and suburban areas, where it becomes more and more difficult to lay cables, while the increase of the number of radio links produce severe interference problems.

4.3. *Communication Links between Satellites*

The use of lasers on satellites has been made possible by the recent progress of laser technology from the point of view of reliability, power efficiency and volume reduction. Space-qualified lasers have been developed [21]. Transmission experiments with carbon dioxide lasers between satellites and between satellites and the earth are planned on the American technological satellites ATS-F and ATS-G. Among other high power light sources, the YAG laser is also interesting but a difficult reliability problem remains to be solved, due to the short lifetime of the arc lamps used to pump these lasers: the studies on the pumping of YAG lasers by electroluminescent diodes can lead to an improved reliability and efficiency [22]. However, if the attenuation problem does not need to be considered in communication links between satellites, where the range is limited only by the aperture of the emitter and receiver antennas, absorption and scattering of light by the atmosphere do remain important in links between a satellite and the earth. So, the place of the lasers seems to be in links between satellites, for instance between geostationary satellites connected in a communication or data-transmission network. The laser experiments with the ATS-F and ATS-G will give information on the feasibility and practical interest of such applications.

5. Conclusion

The bad transmission of light in the atmosphere and the lack of a practical and economical waveguide limit very severely the use of lasers in communication, like they have hindered the use of frequencies above 10 GHz during many years. But lasers are still in a research state and the progress is rapid and continuous in the field of laser sources, – *reliability and efficiency, short pulse emission, semiconductor lasers*, – as well as in the field of light waveguides, especially that of *optical fibers*. So, as the technology of coherent optics develops and as the need of higher capacity links will increase and the conventional radio links become saturated, the interest of the laser for communication purposes will become greater and greater. In a future of ten to fifteen years it seems necessary to use extensively millimetric or optical waves in long distance high capacity trunks: although the laser communication systems are not in the state of development attained for millimetric circular waveguide systems, they can be practically usable before that time. The development of low attenuation optical fibers would make this application possible and would at the same time offer to optical communications possibilities in the field of the local networks of big cities. The realization of these possibilities depends not only on the solution of difficult technical problems, but also on economic conditions which cannot be precisely evaluated at the present state of the art.

6. Acknowledgements

The ideas expressed in the present article do not engage anybody other than the author, who is aware of the controversial nature of the subject. However, he has made use of the results of many authors and he apologizes to those who have not been quoted. He is particularly grateful to *Dr. Gambling*, from the University of Southampton, and to *Dr. Roberts*, from the Post Office Research Center (Great Britain) for recent discussions about optical fibers. He acknowledges the contributions of his co-workers of C.N.E.T., specially *Mrs. Henaff*, on laser sources and associated components, *Mr. Aunis* on atmospheric propagation, *Dr. Marie* on guided wave systems and *Mr. Bourgeat* on the state of the art in millimetric transmission systems.

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Fringing Capacitance in Printed Strip Transmission Line Filters

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Synopsis: Problems associated with odd-mode fringing capacitance, due to the presence of the dielectric slab in a printed strip transmission line filter, are discussed and a simple method for obtaining the correct value is presented. The procedure is illustrated for a single-section filter and satisfactory agreement between theory and experiment is demonstrated.

1. Introduction

Printed strip transmission line filters contain foil strips printed on both sides of a dielectric sheet, supported in air or in dielectric midway between ground plates, as shown in Fig. 1. Here w is the strip width, s is the spacing between two strips or the gap width, b is the spacing between the ground plates, t is the thickness of the dielectric sheet, $\varepsilon_d = \varepsilon_o \varepsilon_{rd}$ is the absolute dielectric constant of the dielectric sheet and $\varepsilon = \varepsilon_o \varepsilon_r$ is the absolute dielectric constant of the medium.

One procedure for designing a strip transmission line filter is to transform the strip line circuit to an equivalent ladder network with lumped elements, which is then compared with prototype filter circuits in order to obtain in terms of the prototype element values the even- and odd-mode characteristic impedances Z_{oe} and Z_{oo} of each strip with respect to ground. The strip width w and the spacing s between the strips are then calculated from Z_{oe} and Z_{oo} using the known values of the strip thickness t and ground plate spacing b.

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2. Characteristic Impedance and Fringing Capacitance

For parallel-coupled open-ended strips, as shown in Fig. 2, the values of Z_{oe} and Z_{oo} have been found to be [1, 2]:

$$\frac{Z_{oek}}{Z_o} = \frac{\Omega_c}{g_1} + \frac{Z_k}{Z_o}\ ;\ k = 1,2,3,\ldots \tag{1a}$$

$$\frac{Z_{ook}}{Z_o} = \frac{\Omega_c}{g_1} - \frac{Z_k}{Z_o} \tag{1b}$$

$$\frac{Z_k}{Z_o} = \frac{2}{g_1}\sqrt{g_k\, g_{k+1}}\ ;\ k = 2,3,4,\ldots \begin{cases} \dfrac{N}{2} & \text{for even } N \\ \dfrac{N+1}{2} & \text{for odd } N \end{cases} \tag{2a}$$

$$\frac{Z_1}{Z_o} = \sqrt{\frac{2g_2}{g_1}} \tag{2b}$$

where

N = number of filter sections

$g_1, g_2, \ldots$ = element values of prototype high-pass filter where an N-section strip line filter corresponds to an $(N+1)$-element prototype filter

Ω_c $= \tan\left[\frac{\pi}{2}\cdot\frac{\omega_c}{\omega_o}\right]$ = normalized cut-off frequency of the prototype filter

ω_c = cut-off frequency of the strip line filter

ω_o = center frequency of the strip line filter for which L is quarter wavelength long

Z_o = terminal impedance of the strip line filter

The various capacitances associated with the strips are shown in Fig. 3, where

C_p = parallel-plate capacitance between strip and ground

C'_f = fringing capacitance from outer strip edge to the closer ground plate and is equal to that of an isolated-strip edge to ground

C'_{fe} = fringing capacitance from inner strip edge to the closer ground plate for even-mode field distribution

C'_{fo} = fringing capacitance between inner strip edge and a metallic wall halfway between the two strips for odd-mode field distribution

The total even- and odd-mode normalized capacitances are hence given by:

$$\frac{C_{oe}}{\varepsilon} = 2\left[\frac{C_p}{\varepsilon} + \frac{C'_{fe}}{\varepsilon} + \frac{C'_f}{\varepsilon}\right] \tag{3a}$$

$$\frac{C_{oo}}{\varepsilon} = 2\left[\frac{C_p}{\varepsilon} + \frac{C'_{fo}}{\varepsilon} + \frac{C'_f}{\varepsilon}\right] \tag{3b}$$

The even- and odd-mode characteristic impedances are related to the total normalized capacitances through the equations [3]:

$$\sqrt{\varepsilon_r}\, Z_{oe} = \frac{376.7}{\dfrac{C_{oe}}{\varepsilon}} \; ; \; \sqrt{\varepsilon_r}\, Z_{oo} = \frac{376.7}{\dfrac{C_{oo}}{\varepsilon}} \tag{4}$$

The normalized coupling capacitance between the strips is given by [3]:

$$\frac{\Delta C}{\varepsilon} = \frac{376.7}{2\sqrt{\varepsilon_r}}\left[\frac{1}{Z_{oo}} - \frac{1}{Z_{oe}}\right] =$$

$$= \frac{1}{2}\left[\frac{C_{oo}}{\varepsilon} - \frac{C_{oe}}{\varepsilon}\right] = \frac{C'_{fo}}{\varepsilon} - \frac{C'_{fe}}{\varepsilon} \tag{5a}$$

while the normalized strip width is [3]:

$$\frac{w}{b} = \frac{1}{2}\left(1 - \frac{t}{b}\right)\left[\frac{C_{oe}}{2\varepsilon} - \frac{C'_{fe}}{\varepsilon} - \frac{C'_f}{\varepsilon}\right] \tag{5b}$$

which is modified, if $\left(\frac{w}{b}\right) < 0.35\left(1 - \frac{t}{b}\right)$.

For the strip line configuration of Fig. 1, the values of the even- and odd-mode fringing capacitances have been derived by Cohn [4]. There it is stated that if $\frac{s}{t} > 10$, the following equations will give satisfactory results:

$$\frac{C'_{fe}}{\varepsilon}\left(\frac{t}{b}, \frac{s}{b}\right) = \frac{C'_{fe}}{\varepsilon}\left(0; \frac{s}{b}\right) \cdot \frac{\dfrac{C'_f}{\varepsilon}\left(\dfrac{t}{b}\right)}{\dfrac{C'_f}{\varepsilon}(0)} \tag{6a}$$

$$\frac{C'_{fo}}{\varepsilon}\left(\frac{t}{b}, \frac{s}{b}\right) = \frac{C'_{fo}}{\varepsilon}\left(0; \frac{s}{b}\right) \cdot \frac{\dfrac{C'_f}{\varepsilon}\left(\dfrac{t}{b}\right)}{\dfrac{C'_f}{\varepsilon}(0)} \tag{6b}$$

However, if $\frac{s}{t} \leqslant 10$, equation (6a) still holds, but equation (6b) must be modified to the following expression:

$$\frac{C'_{fo}}{\varepsilon}\left(\frac{t}{b}, \frac{s}{b}\right) = \frac{C'_{fo}}{\varepsilon}\left(0; \frac{s}{b}\right) + \frac{\varepsilon_d}{\varepsilon} \cdot \frac{Z_o\left(\frac{s}{t}, 0\right)}{376.7} \tag{7}$$

where

$Z_o\left(\frac{s}{t}, 0\right)$ = characteristic impedance of a single strip in the dielectric ε, whose ground-plate spacing is t, strip width is s and thickness is zero.

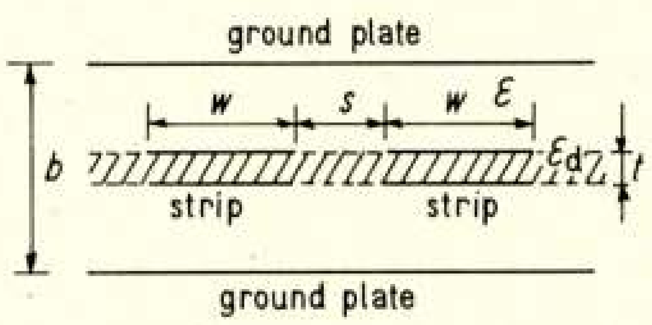

Fig. 1. Parallel-coupled printed strip-line filter (end view).

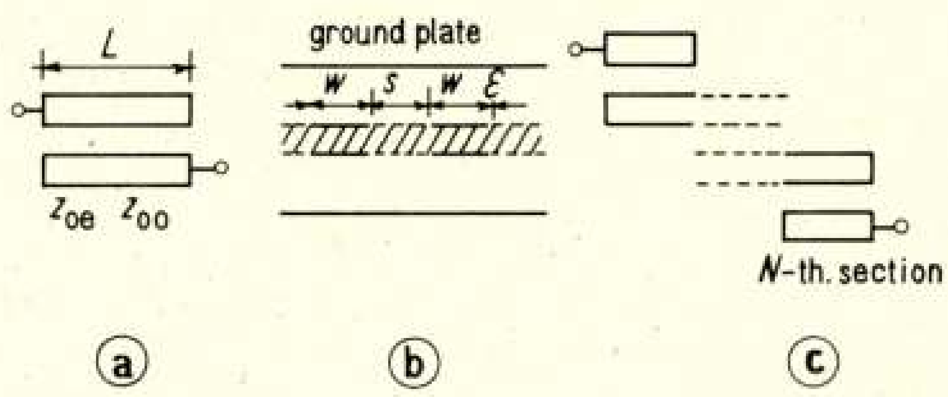

Fig. 2. a. Single section, top view; **b.** Single section, end view; **c.** *N* section, top view.

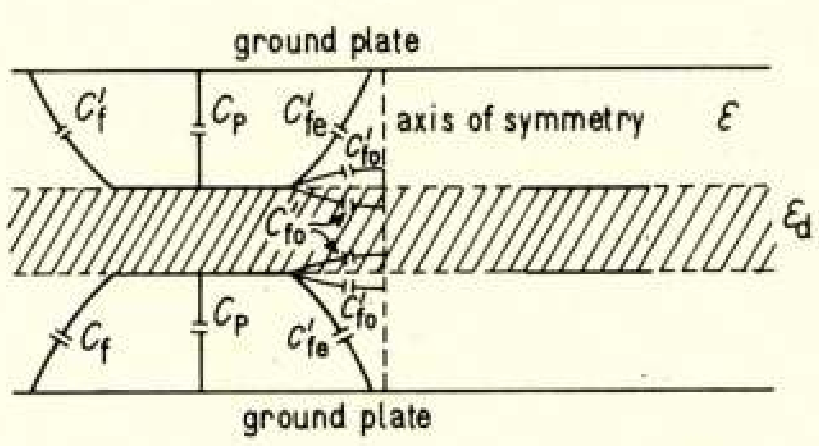

Fig. 3. Various fringing and parallel-plate capacitances for a filter section.

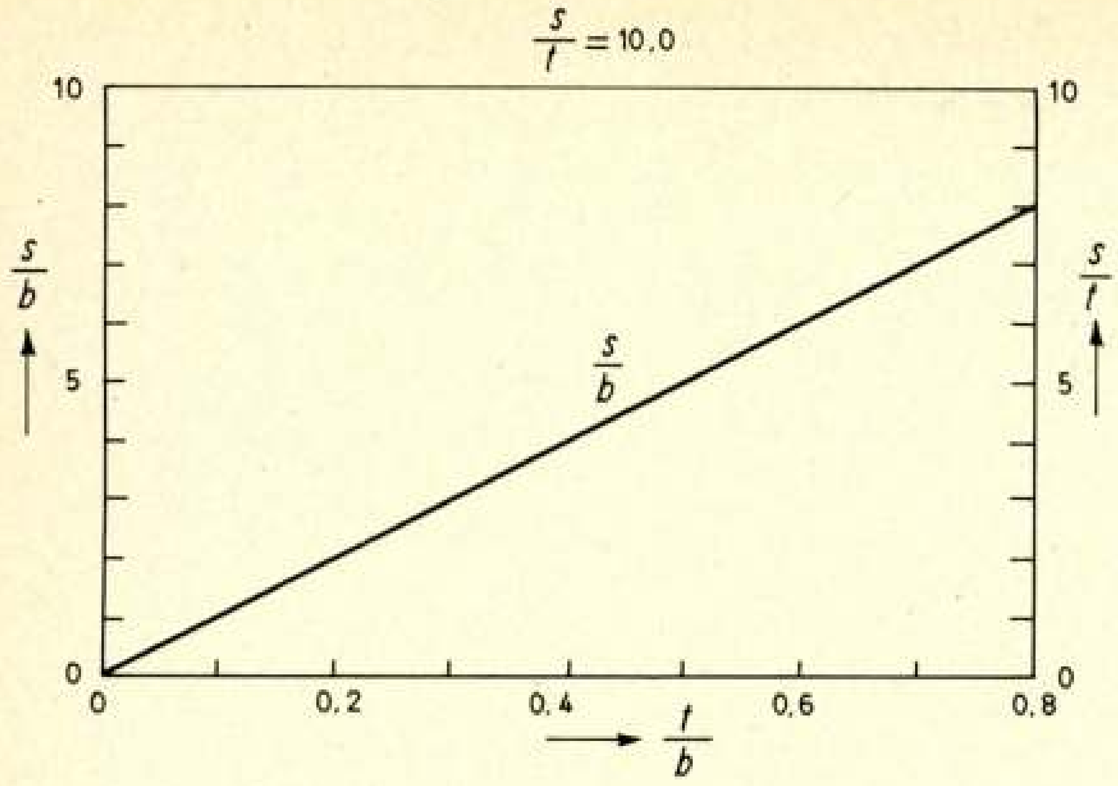

Fig. 4. $\frac{s}{b}$ as a function of $\frac{t}{b}$, for $\frac{s}{t} = 10.0$.

A plot of $\frac{s}{b}$ versus $\frac{t}{b}$ for $\frac{s}{t} = 10$ is shown in Fig. 4. For a given $\frac{t}{b}$, the corresponding value of $\frac{s}{b}$ gives the maximum gap width for which equation (7) is applicable. For larger gap widths, equation (6b) is valid. Fig. 5 shows a plot of $\frac{C'_{fe}}{\varepsilon}$, $\frac{C'_{fo}}{\varepsilon}$ and $\frac{\Delta C}{\varepsilon}$ versus $\frac{s}{b}$ corresponding to $\frac{t}{b} = 0.17$, $\varepsilon_{rd} = 2.1$ and $\varepsilon_r = 1.0$, where $\frac{C'_{fo}}{\varepsilon}$ has been calculated from both equations (6b) and (7). Note that when $\frac{C'_{fo}}{\varepsilon}$ is calculated from equation (6b), as shown

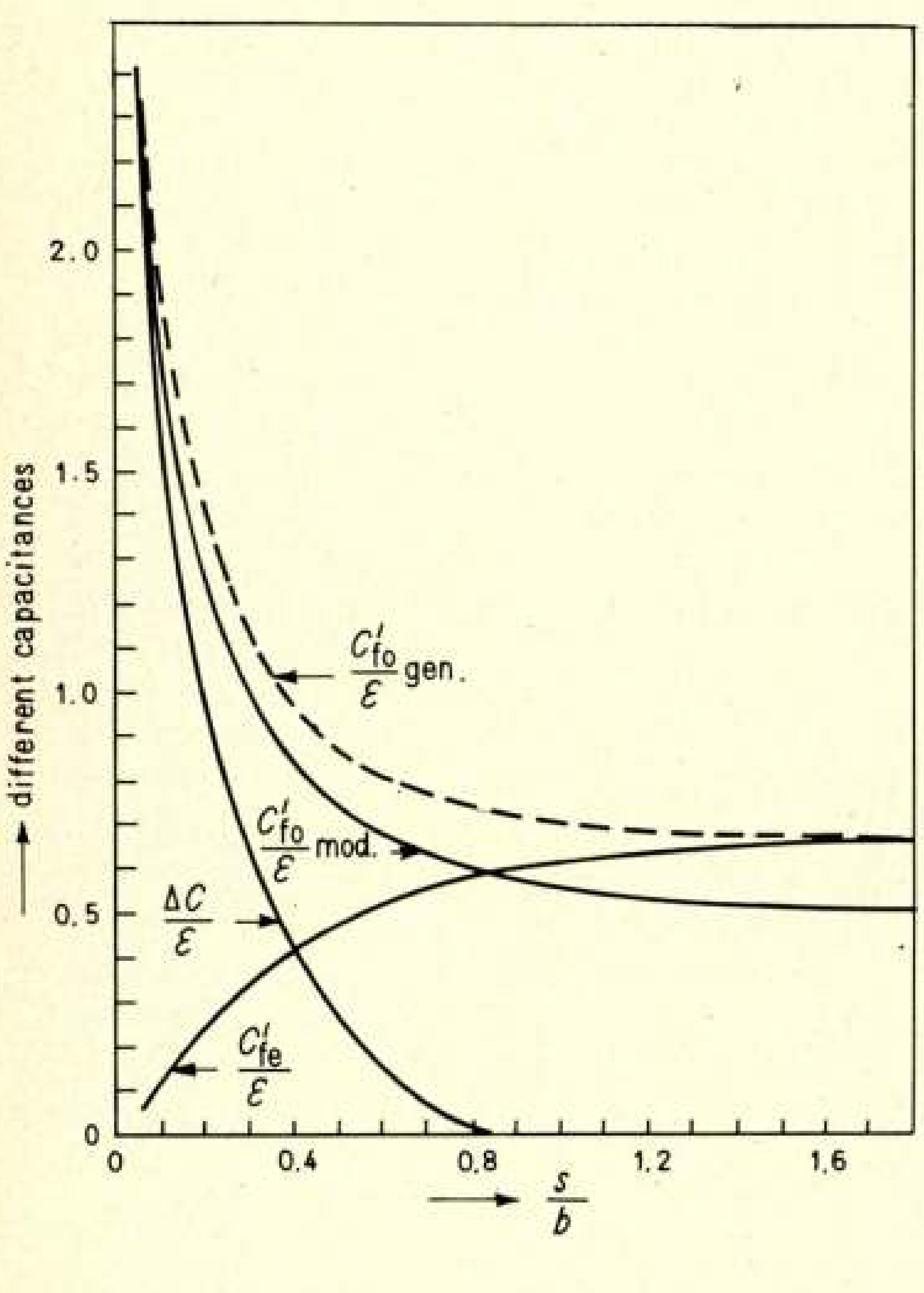

Fig. 5. $\frac{C'_{fe}}{\varepsilon}, \frac{C'_{fo}}{\varepsilon}, \frac{\Delta C}{\varepsilon}$ as a function of $\frac{s}{b}$, for $\frac{t}{b} = 0.17$.

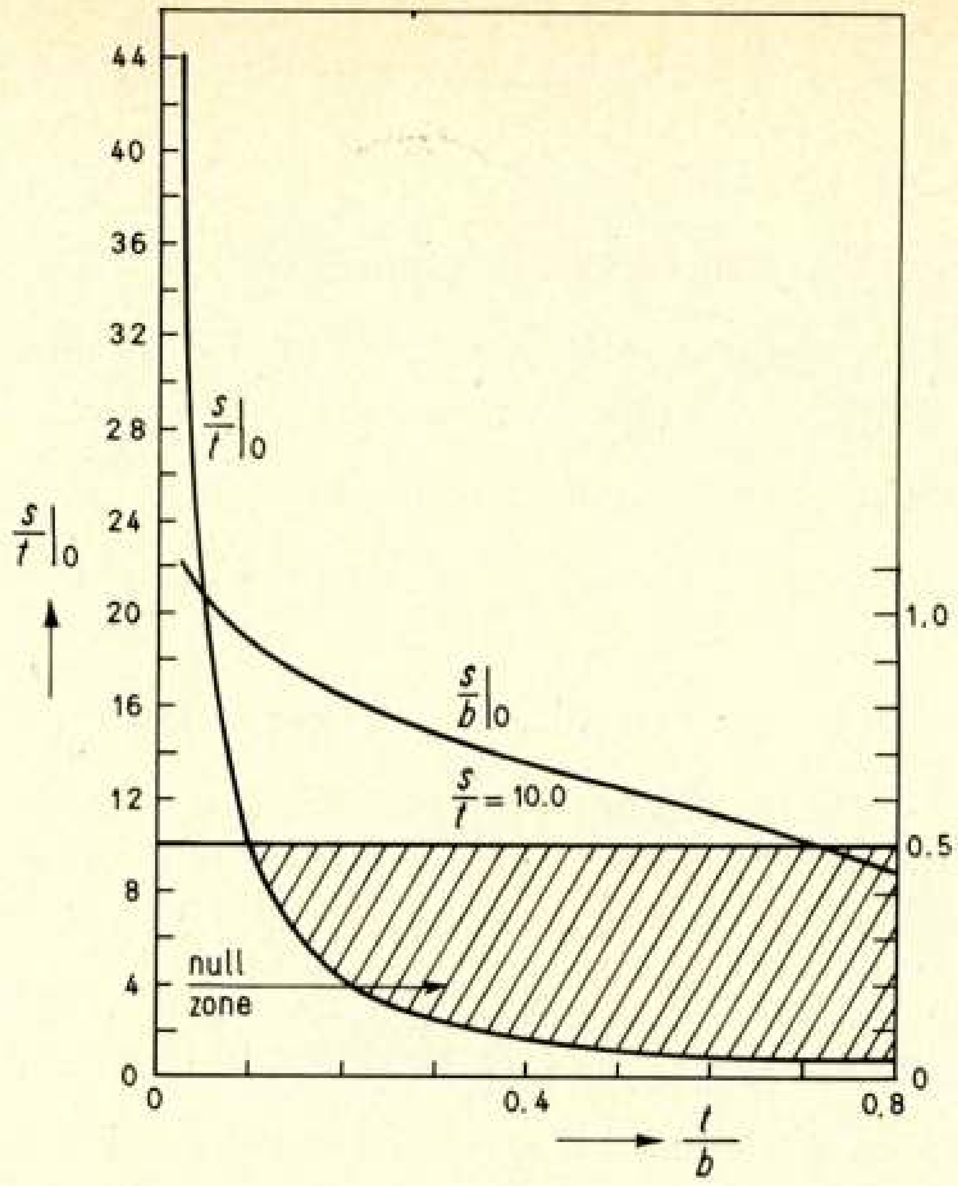

Fig. 6. $\left.\frac{s}{b}\right|_0$ and $\left.\frac{s}{t}\right|_0$ as functions of $\frac{t}{b}$.

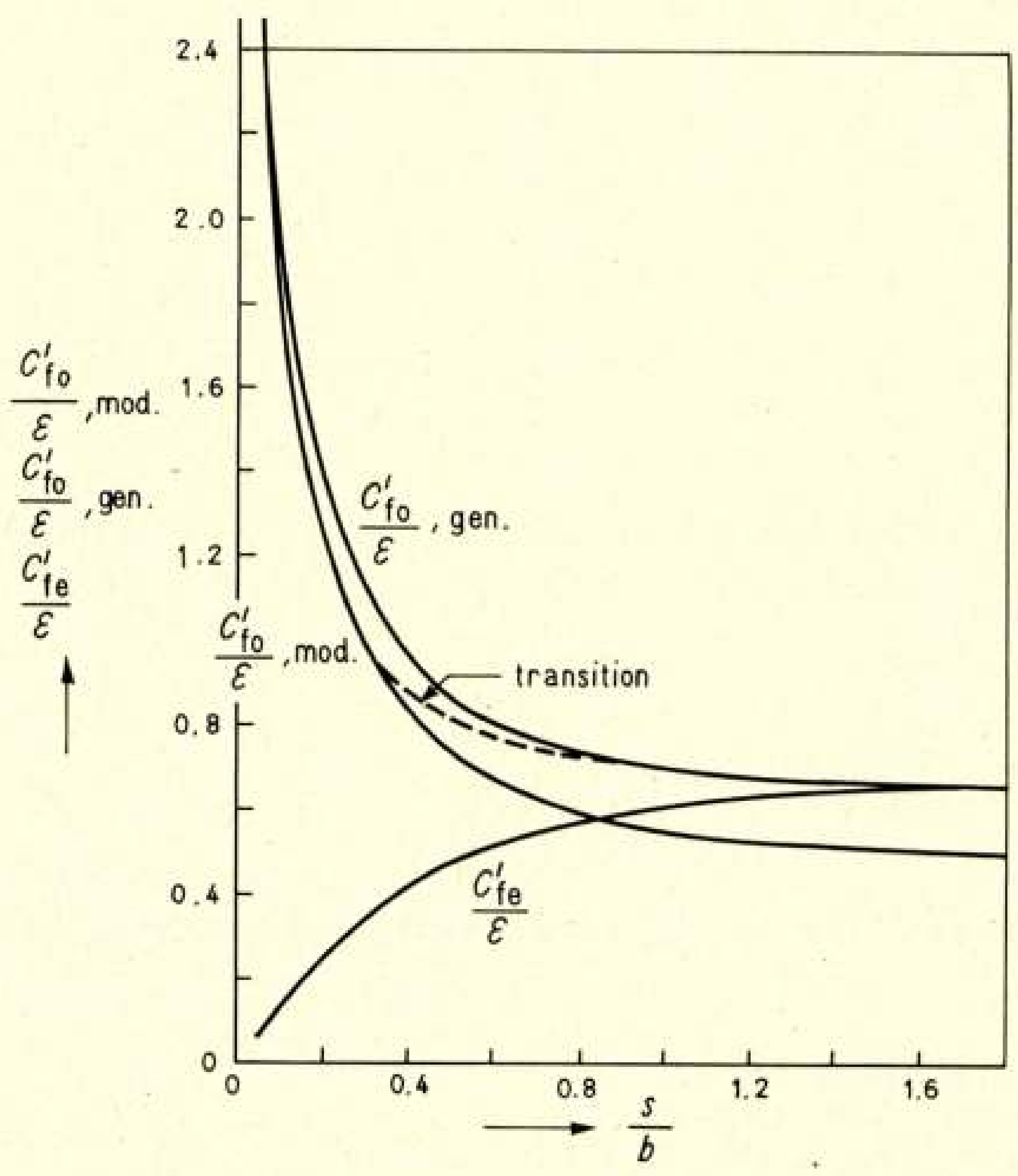

Fig. 7. General and modified plots for $\frac{C'_{fo}}{\varepsilon}$ and $\frac{C'_{fe}}{\varepsilon}$ versus $\frac{s}{b}$, for $\frac{t}{b} = 0.17$.

by the dotted line in Fig. 5, both $\frac{C'_{fo}}{\varepsilon}$ and $\frac{C'_{fo}}{\varepsilon}$ curves merge into a single curve at $\frac{s}{b} \approx 2.0$ and correspond to the value of $\frac{C'_{fe}}{\varepsilon}$ for $\frac{t}{b} = 0.17$. In other words, the two strips behave as if they were isolated ones [4].

However, when $\frac{C'_{fo}}{\varepsilon}$ is calculated from equation (7), the two curves intersect at $\frac{s}{b} = 0.85$, corresponding to a value of $\frac{s}{t} = 5$. Since ΔC is a positive quantity, it appears that for $\frac{s}{b} \geq 5$, there

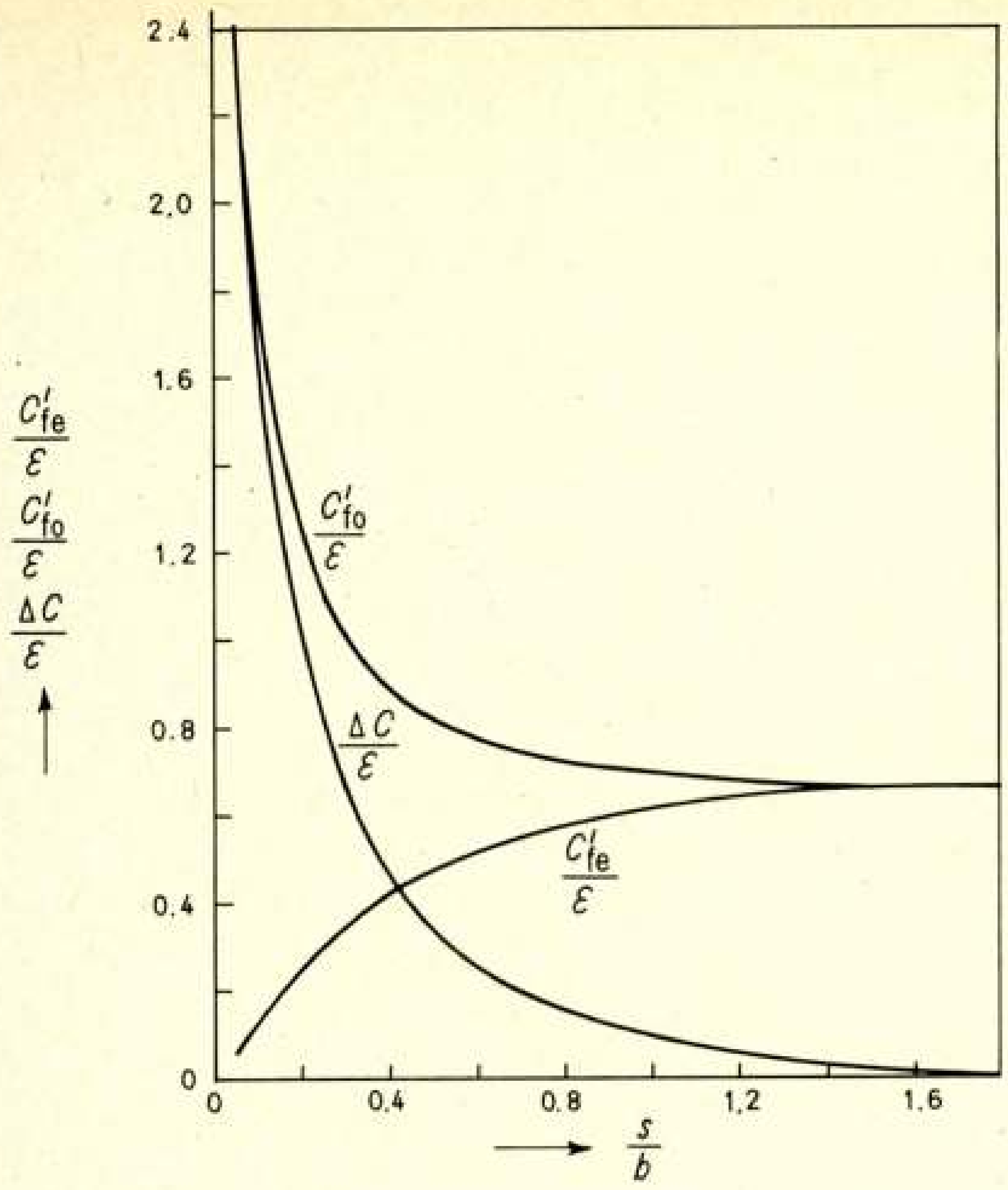

Fig. 8. $\frac{C'_{fo}}{\varepsilon}$ (combined plot), $\frac{C'_{fe}}{\varepsilon}$ and $\frac{\Delta C}{\varepsilon}$ versus $\frac{s}{b}$, for $\frac{t}{b} = 0.17$.

will be no coupling between the strips. Using different values of $\frac{t}{b}$ we can plot a number of such graphs and obtain the corresponding values of $\left.\frac{s}{b}\right|_0$ and $\left.\frac{s}{t}\right|_0$ for which $\frac{\Delta C}{\varepsilon} = 0$. The result is shown in Fig. 6, together with the horizontal straight line representing $\frac{s}{t} = 10.0$.

Fig. 6 shows that the validity of equation (7) depends largely on $\frac{t}{b}$. The shaded area can be called the 'null zone', because for any value of $\frac{s}{t}$ in this area there is no coupling capacitance between the strips, even though the $\frac{t}{b}$-values are less than 10.0.

It appears that for $\frac{t}{b} < 0.1$ equation (7) applies directly, while for $\frac{t}{b} > 0.1$ it can only be used if $\frac{s}{t}$ does not fall in the null zone. Moreover, to ensure a good coupling, a reasonable amount of coupling capacitance between the strips is needed. Hence, before equation (7) is used, we must be sure that $\frac{s}{t}$ is well below the null zone.

Several questions may arise at this stage, namely how far should $\frac{s}{t}$ be below the null zone to obtain a reasonable value of ΔC and is there a definite way to indicate the location of $\frac{s}{t}$?

Although $\frac{t}{b}$ is known beforehand, $\frac{s}{t}$ is not known until $\frac{s}{b}$ is determined. But $\frac{s}{b}$ is obtained from the graph prepared from $\frac{C'_{fe}}{\varepsilon}$ and $\frac{C'_{fo}}{\varepsilon}$, for which $\frac{C'_{fo}}{\varepsilon}$ must be known. However, it is not clear when the general and when the modified equation should be used for this purpose. To overcome this difficulty, we note that for a given strip thickness, when $\frac{s}{b} = \left.\frac{s}{b}\right|_0$, there is no coupling between the strips, and we must use the general equation. Also, as can be seen from Fig. 5, in the vicinity of $\frac{s}{b} = \left.\frac{s}{b}\right|_0$ the value of $\frac{\Delta C}{\varepsilon}$ is very small and hence we should not use the modified equation when $\frac{s}{b}$ is slightly less than $\left.\frac{s}{b}\right|_0$. To elaborate further we refer to Fig. 7, where $\frac{C'_{fo}}{\varepsilon}$ calculated from the general equation (6b) and the modified equation (7), and $\frac{C'_{fe}}{\varepsilon}$ have been plotted versus $\frac{s}{b}$, for $\frac{t}{b} = 0.17$ Here we see that the modified $\frac{C'_{fo}}{\varepsilon}$-curve crosses the $\frac{C'_{fe}}{\varepsilon}$-curve at $\frac{s}{b} = 0.85$. For the region $\frac{s}{b} \geqslant 0.85$ we must use the general curve, while for the region $\frac{s}{b} < 0.85$ we may use the modified curve as far as possible, but without causing a considerable reduction in $\frac{\Delta C}{\varepsilon}$, in order to avoid weak coupling.

Obviously there exists a region with a transition from the modified to the general curves, which begins somewhere before $\frac{s}{b} = 0.85$ and is completed at that point. To obtain this transition part we extend the general curve backwards in such a way that the shortest possible extension will provide a smooth continuous curve with the modified curve as shown by the dotted line in Fig. 7. The resulting curve is a combined plot of equations (6b) and (7) and contains part of the modified curve in the smaller gap region and is therefore valid for all values of $\frac{s}{b}$.

The combination curve for $\frac{C'_{fo}}{\varepsilon}$ thus obtained is shown in Fig. 8, together with a plot of $\frac{C'_{fe}}{\varepsilon}$ and the corresponding $\frac{\Delta C}{\varepsilon}$, and is applicable for all values of $\frac{s}{b}$. Curves prepared in this

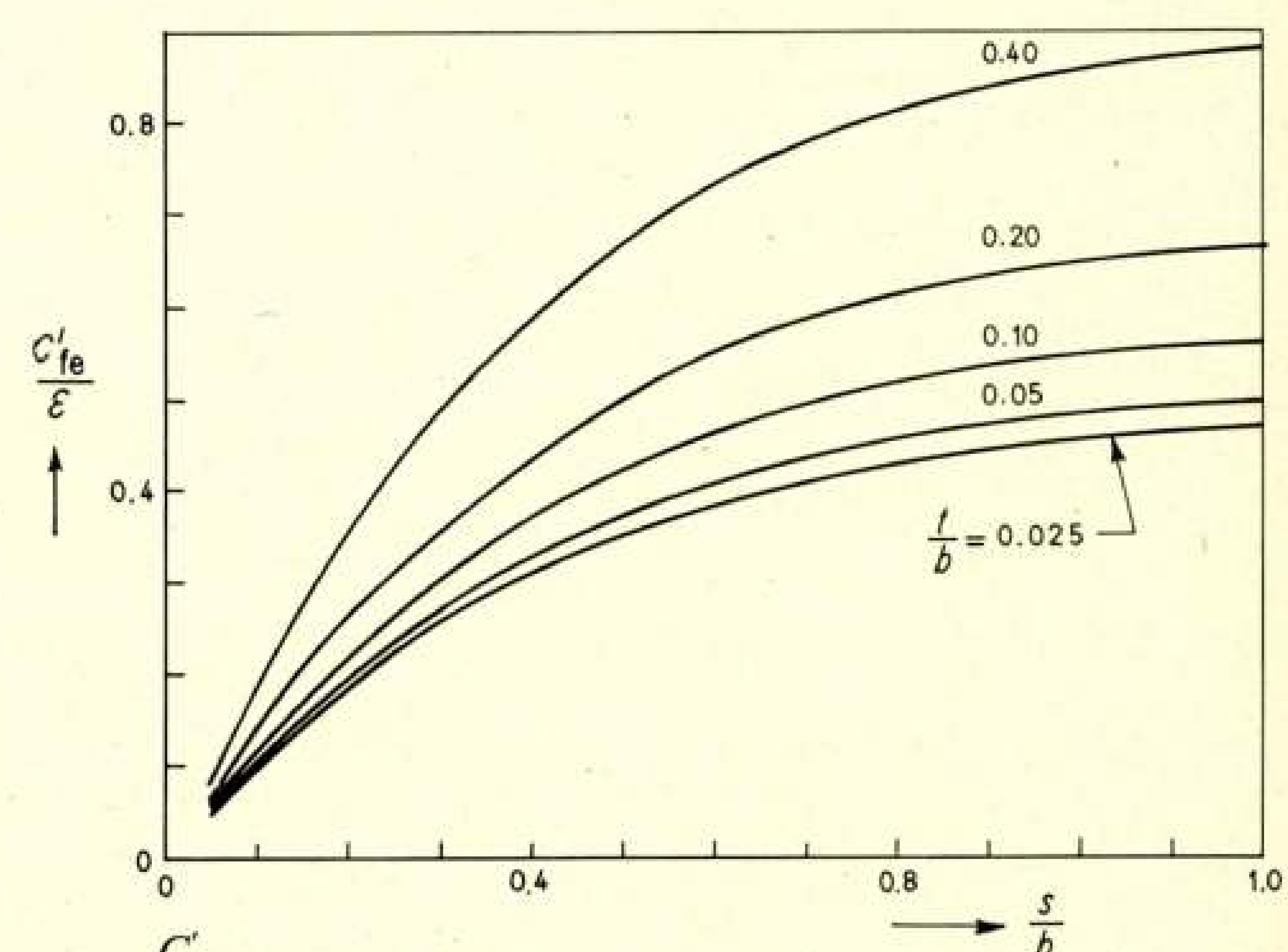

Fig. 9. $\frac{C'_{fe}}{\varepsilon}$ versus $\frac{s}{b}$, for various values of $\frac{t}{b}$.

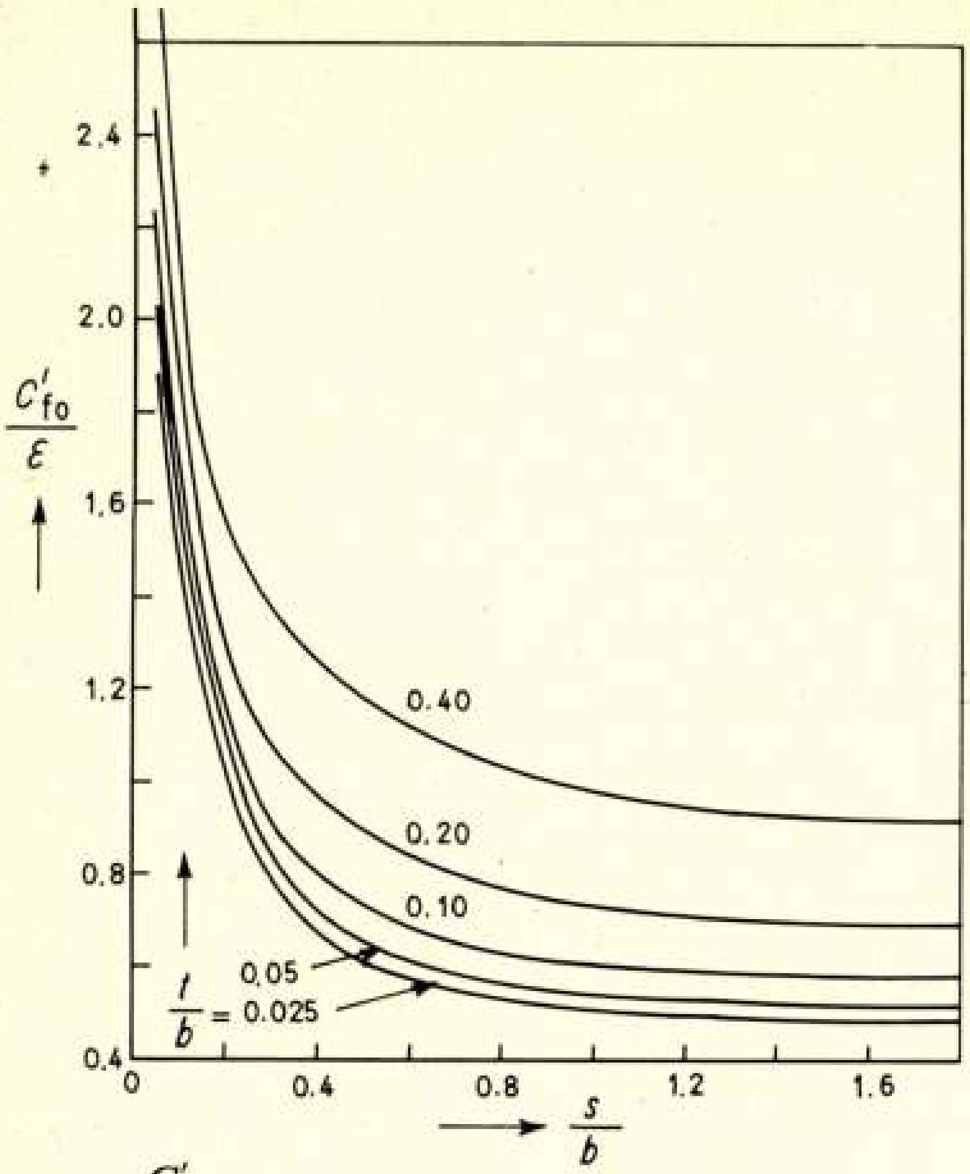

Fig. 10. $\frac{C'_{fo}}{\varepsilon}$ versus $\frac{s}{b}$ for various values of $\frac{t}{b}$.

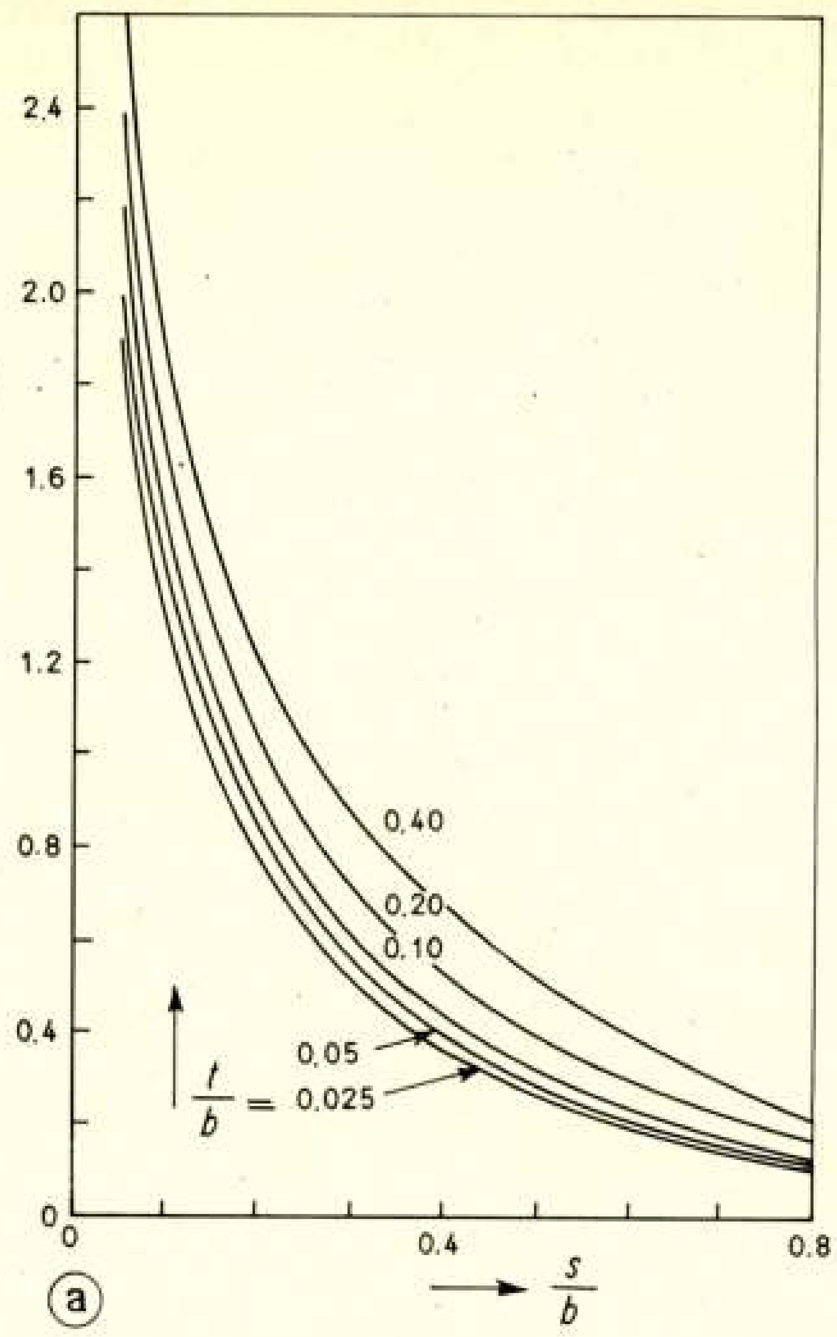

Fig. 11a. $\frac{\Delta C}{\varepsilon}$ versus $\frac{s}{b}$, for various values of $\frac{t}{b}$.

manner for different values to $\frac{t}{b}$ are shown in Figs. 9, 10 and 11 which may be used to design printed strip line filters with dielectric sheets of various thicknesses. The method for finding the transit between wide-strip and narrow-strip formulae, adopted here is somewhat similar to that of *Cohn* [5].

3. Illustration of the Design Procedure

As an example to illustrate the procedure, a single-section Butterworth filter was constructed with the dielectric sheet supported in air, midway between the ground plates, using a 1.7 mm thick teflon sheet ($\varepsilon_{rd} = 2.1$) clad with copper foil on both sides. The ground plate spacing b was selected to be 1.0 cm.

Since a single-section strip line filter corresponds to a 2-element high pass prototype filter, we have

$$g_1 = g_2 = 0.707; \quad \frac{Z_1}{Z_0} = 1.0$$

A fractional bandwidth of 41% with center frequency at 2.7 GHz was chosen for which $\Omega_c = 3.024$. Hence

$$\frac{Z_{oe}}{Z_o} = 5.278; \quad \frac{Z_{oo}}{Z_o} = 3.278$$

Assuming that $Z_o = 22\,\Omega$, we obtain

$$Z_{oe} = 116\,\Omega; \; Z_{oo} = 72\,\Omega$$

Since for air $\varepsilon_r = 1.0$, we also have

$$\frac{C_{oe}}{\varepsilon} = 3.25; \quad \frac{C_{oo}}{\varepsilon} = 5.23$$

hence

$$\frac{\Delta C}{\varepsilon} \simeq 1.0$$

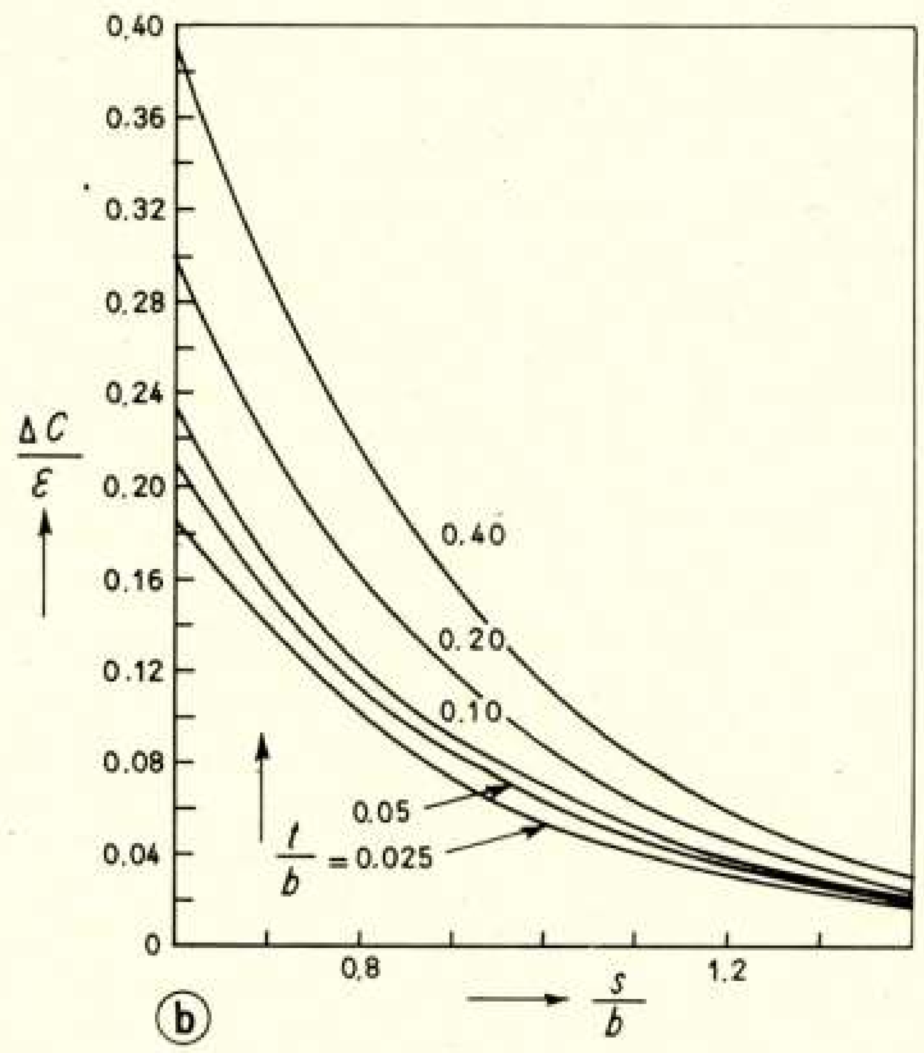

Fig. 11b. $\frac{\Delta C}{\varepsilon}$ versus $\frac{s}{b}$, for various values of $\frac{t}{b}$.

Using Fig. 10 we obtain $\frac{s}{b} = 0.2$ and $\frac{C'_{fe}}{\varepsilon} = 0.25$, corresponding to $\frac{\Delta C}{\varepsilon} = 1.0$. For $\frac{t}{b} = 0.17$, $\frac{C'_f}{\varepsilon} \approx 0.655$ [3, 5]. Hence, equation (5b) gives $\frac{w}{b} \approx 0.3$.

The length of the strip lines was made 27.8 mm, corresponding to one quarter wavelength at 2.7 GHz.

We have assumed that $Z_o = 22\,\Omega$. This has been transformed to a line impedance R of 50 Ω by means of double quarter-wave transformers whose strip widths w_1 and w_2 were obtained from the impedances Z_1, Z_2 [5, 6] with the following calculated results:

$$Z_1 = \left[22^3 \times 50\right]^{\frac{1}{4}} = 27\ \Omega\ ;\ \frac{w_1}{b} = 2.3$$

$$Z_3 = \left[22 \times 50^3\right]^{\frac{1}{4}} = 41\ \ \Omega\ ;\ \frac{w_2}{b} = 1.35$$

$$R = 50\ \Omega; \qquad \frac{w_R}{b} = 1.0$$

where w_R is the width of the strip line corresponding to R. Thus all the dimensions have been found to be

$s = 2.0$ mm; $\quad w_1 = 23.0$ mm; $\quad w_R = 10.0$ mm

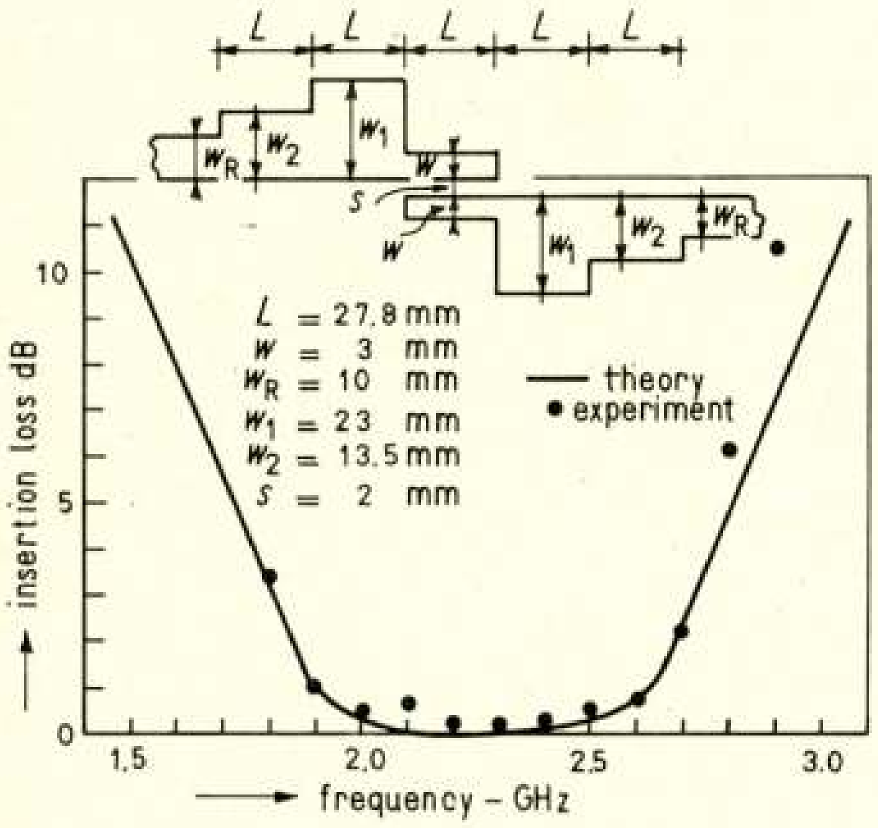

Fig. 12. Single-section filter and its response.

The circuit was drawn on both sides of the teflon sheet and the unwanted part of the copper foil was taken off. The final circuit is shown in Fig. 12 together with the response. The solid line shows the theoretical attenuation calculated from the relation

$$|t|^2_{\text{TEM}} = \frac{1}{1 + \left(\frac{\Omega_c}{\Omega}\right)^{2n}} \qquad (8)$$

where:

$|t|$ = transmission function of the network,

n = number of reactive elements in the high pass prototype filter, and

Ω = $\tan\left[\frac{\pi}{2} \cdot \frac{\omega}{\omega_0}\right]$ variable frequency of the prototype filter.

The resulting error in the bandwidth is obtained from Fig. 12 and appears to be approximately 5%. This is in good agreement with theory [7], which predicts an expected error of approximately 6%.

As expected, the center frequency is seen to be 2.27 GHz instead of 2.7 GHz. The quarter wavelength L' corresponding to 2.27 GHz is 33.0 mm. Hence the difference between the physical and electrical line length is $d = 33.0 - 27.8 = 5.2$ mm.

To obtain the design center frequency of 2.7 GHz, the line

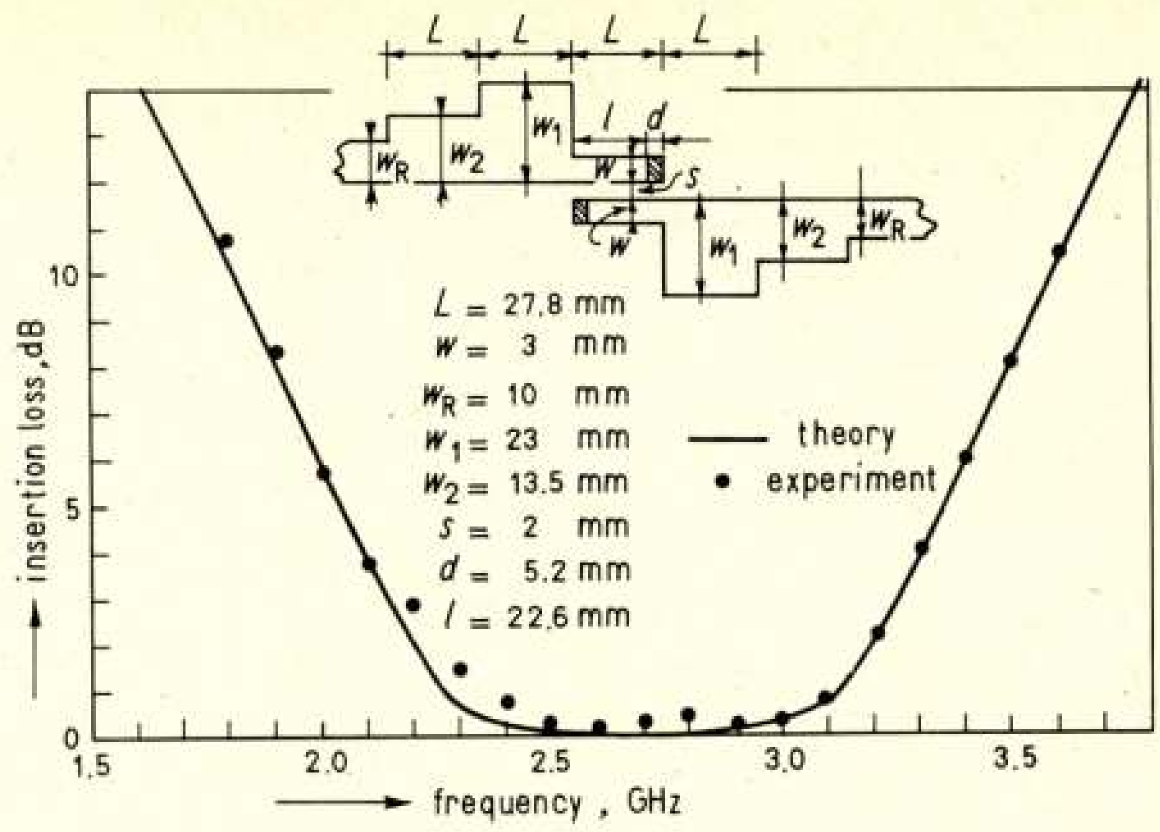

Fig. 13. Single-section filter and its response; end shortened.

lengths were shortened by 5.2 mm. The resulting response is shown in Fig. 13, which indicates that the correct center frequency has been obtained.

To predict the value of d, *Cohn* [8] has suggested a formula given by:

$$d = k \left|\frac{C'_f}{\varepsilon} \cdot \frac{b}{2}\right| \qquad (9)$$

where k is a constant smaller than unity; k has been found experimentally to be 0.75. For the different ratios $\frac{t}{b}$, the values of $\frac{C'_f}{\varepsilon}$ are obtained from [3, 5]. For strips with zero thickness, the value of d in equation (9) with $k = 0.75$ was found to be the increase in electrical length of the line due to the fringing capacitance of its end. For the present filter $\left(\text{with } \frac{t}{b} = 0.17\right)$ $d = 5.2$ mm, $b = 10$ mm, $\frac{C'_f}{\varepsilon} = 0.655$, and hence $k = 1.59$.

It then appears that, although $k = 0.75$ is the suitable value for strips with zero thickness, this value should be modified for strips with finite thickness.

4. Conclusions

Examination of the results shown in Figs. 12 and 13 learns that a reasonably good agreement exists between our theory and experiments, in spite of the various approximations in the theory and the experimental errors in constructing the filter.

We have therefore developed a reliable curve for obtaining the odd-mode fringing capacitance of a printed strip line filter, that leads to the filter dimensions s and w. This was achieved by using two different equations for this fringing capacitance, one valid for a narrow gap region and the other for wide gaps. These were not distinctly identified due to the presence of a null zone caused by the strip thickness.

Since the value of $\frac{s}{t}$ just below the null zone corresponds to a value of $\frac{s}{b}$ nearly equal to $\left.\frac{s}{b}\right|_0$, the coupling capacitance between the strip lines, as seen from Fig. 5, is very small, which will result in a very weak coupling. Consequently, for a reasonable value of coupling capacitance, $\frac{s}{t}$ should be well below the null zone and in fact the lower its value below the null zone, the larger is the coupling capacitance. For this reason we derived a continuous plot of the odd-mode fringing capacitance valid over the entire range of gapwidths, thus eliminating the uncertainty of locating the value of $\frac{s}{t}$ below the null zone. This is shown in Figs. 7 and 8 and is extended to various normalized strip thicknesses in Figs. 9, 10 and 11.

Since the electrical length is larger than the physical length of the strip lines, due to the fringing capacitance at the end of the lines, the center frequency obtained is lower than the design value. In order to obtain the design center frequency, it is necessary to shorten the length L by the amount d given in equation (9), except that the empirical value of k found by *Cohn* [8] for zero thickness strips should be modified for strips with finite thickness. Although we have suggested another empirical value ($k = 1.59$), based on experiment over our test filter of $t = 1.7$ mm, there is no guarantee that this value is adequate for other values of t. Further theoretical and experimental work seems necessary to predict the proper value of d for any specified value of t. Since the circuit is drawn on both sides of the dielectric sheet, it is important in future work to take particular care during the drawing to ensure that the circuit on one side is the mirror image of that on the other side.

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