although it has more recently been found that some modifications are necessary for high accuracy (within 1 per cent) to be achieved.[8] Closed formulae for w/h will be given in Section 3.5.

3.3.4 Wavelength λ_g and physical length l

For any propagating wave the velocity is given by the appropriate frequency–wavelength product. In free space we have $c = f\lambda_0$ and in the microstrip the velocity is $v_p = f\lambda_g$. Substituting these products into eqn (3.9) we obtain

$$\epsilon_{eff} = \left(\frac{\lambda_0}{\lambda_g}\right)^2$$

or

$$\lambda_g = \frac{\lambda_0}{\sqrt{\epsilon_{eff}}} \qquad (3.14)$$

where λ_0 is the free-space wavelength.

More conveniently, where the frequency is given in gigahertz and denoted by F, the wavelength can be expressed directly in millimetres as follows:

$$\lambda_g = \frac{300}{F\sqrt{\epsilon_{eff}}}\ \text{mm} \qquad (3.15)$$

The physical length l of a microstrip line to yield a specified electrical length θ (in degrees) is easily determined. In Chapter 1 (Section 1.3) we derived the phase coefficient β, and βl is equal to this electrical length in radians, i.e.

$$\beta l = \theta$$

and hence

$$\frac{2\pi l}{\lambda_g} = \theta$$

With θ in degree this gives

$$l = \frac{\theta\lambda_g}{360} \qquad (3.16)$$

Thus, with λ_g evaluated using eqn (3.15), we can simply find l.

3.4 APPROXIMATE GRAPHICAL SYNTHESIS

Presser[9] has devised a graphical technique for the analysis or synthesis of microstrip lines. The method is quick and useful where errors of a few per cent can be tolerated and where a calculator is not readily available. This technique is based upon the work of Wheeler[6, 7] and thus it uses the static-TEM approach which is applicable for frequencies up to a few gigahertz. The 'design curves' given by Presser are reproduced in Figure 3.7. Notice that the width-to-height or 'shape' ratio *w/h* and filling factor *q* are both plotted to a base of the *air-spaced* characteristic impedance Z_{01}. This helps to make the graph fairly universal, as the following design synthesis steps will indicate:

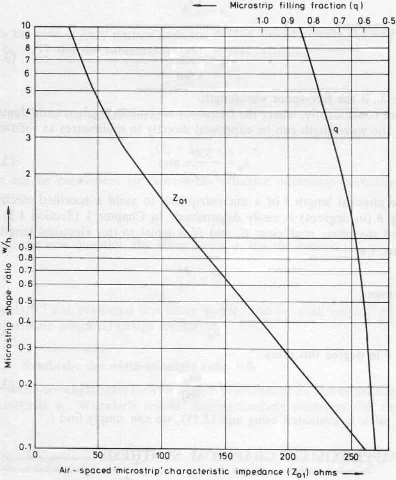

Fig. 3.7. 'General' curves for the analysis or synthesis of microstrip. (Reproduced by permission of *Microwaves* from Presser,[9] Figure 2.)

(a) Make the initial, very rough, assumption—$\epsilon_{eff} \simeq \epsilon_r$—to obtain starting values.
(b) Calculate the air-spaced characteristic impedance approximately, from eqn (3.10), with $\epsilon_{eff} \simeq \epsilon_r$:

$$Z_{01} \simeq \sqrt{\epsilon_r} Z_0$$

(c) Use the general two-curve graph (Figure 3.7) to find w/h applicable to this Z_{01}, and also note the corresponding value of the microstrip filling factor q.
(d) Hence calculate the up-dated value of ϵ_{eff} using eqn (3.12):

$$\epsilon_{eff} = 1 + q(\epsilon_r - 1)$$

This now ends one iteration. Steps (b) to (d) must be repeated, using the progressively improved values of ϵ_{eff} (instead of ϵ_r in steps i and ii). Fast convergence is generally obtained here and only two or three iterations are usually necessary before ϵ_{eff} is finally within about 1 per cent of its previous value; i.e. convergence has occurred.

The final value of w/h, and hence the width w, is of course the value appropriate to the final Z_{01}. Lastly, the wavelength must be calculated using eqn (3.15). The *static-TEM* part of the microstrip design procedure is then complete using this graphical technique.

However, *any* graphical approach will inevitably involve errors of several per cent and also clearly cannot form part of a computer-aided design (CAD) algorithm. This form of graphical technique is mainly suitable for approximate guidance purposes. Most microstrip MIC design work necessarily proceeds on a CAD basis and demands relatively high accuracy (typically better than 1 per cent). Therefore closed formulae are very useful for synthesis; in the next section suitable formulae are presented.

3.5 FORMULAE FOR ACCURATE STATIC-TEM CALCULATIONS

Closed formulae are highly desirable for use in microstrip calculations for the following reasons:

(a) A fairly high accuracy is achievable.
(b) Fast CAD algorithms can be implemented, including the following.
(c) Incorporation of static-TEM formulae in frequency-dependent calculations for higher-frequency design (Chapter 4).

Various workers have reported formulae for microstrip calculations.[7,8,10,11] Owens[8] carefully investigated the ranges of applicability of many of the expressions given by Wheeler,[7] comparing calculated results with numerical