

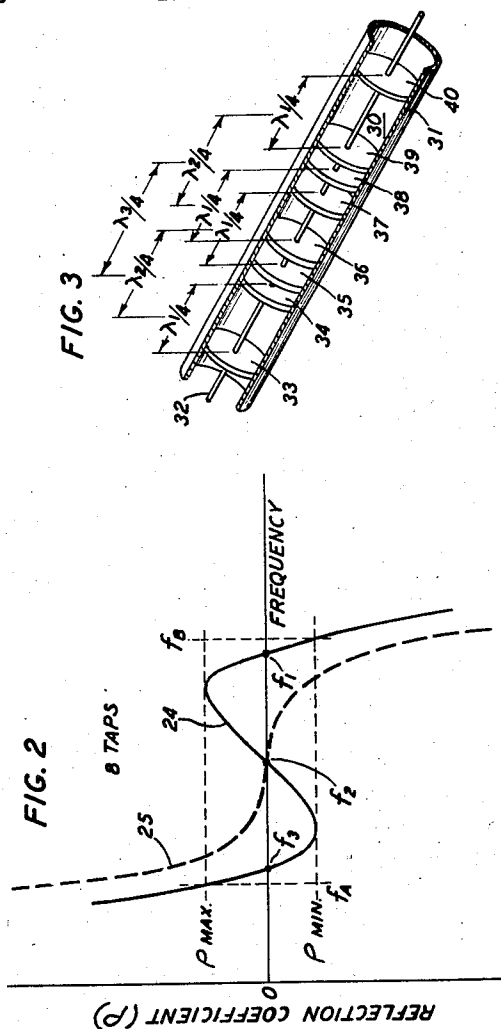
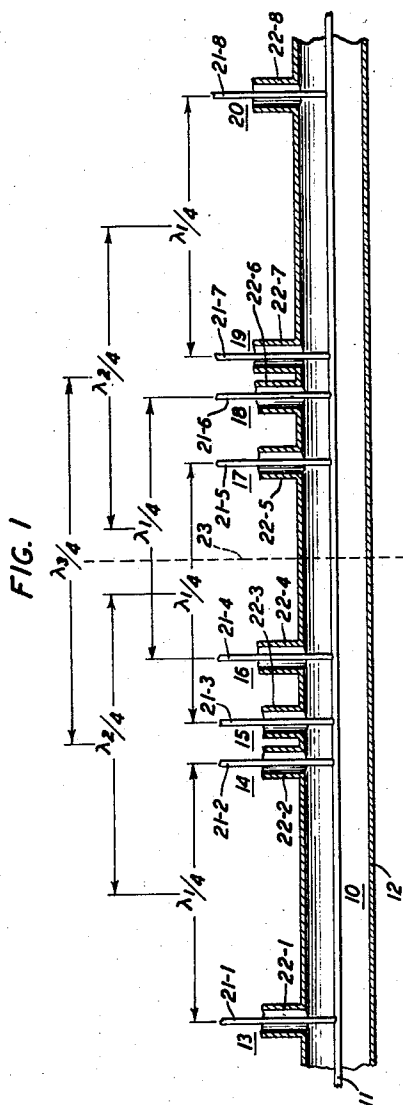
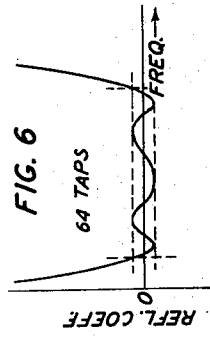
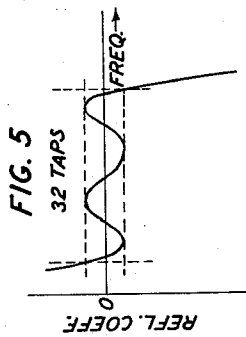
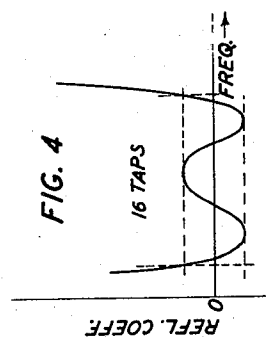
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WAVE TRANSMISSION SYSTEM

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2,896,178

WAVE TRANSMISSION SYSTEM

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This invention relates to electromagnetic wave transmission and distribution systems and, more particularly, to broadband transmission in such systems.

Since the advent of television and other broadband signaling systems, the use of ultra-high-frequency transmission lines such as wave guides, dielectric guides, coaxial lines and other electromagnetic wave-confining transmission structures has become increasingly widespread. These transmission lines are inherently capable of supporting electromagnetic wave energy extending over an extremely wide range of frequencies and hence are eminently suitable for such broadband signaling. Unfortunately, however, it often becomes necessary to include discontinuities of one sort or another in the wave propagating path of such a line. It is, for example, sometimes necessary to remove energy from the transmission structure by means of probes, apertures or junctions, each of which constitutes a discontinuity in the wave propagation path. Similarly, in the interest of minimizing dielectric losses, the mechanical support required for the center conductor of a coaxial line is often provided by means of dielectric "beads" spaced apart at intervals along the length of the line, which beads also constitute discontinuities. The effect of any of these discontinuities is to cause reflections of a transmitted wave, making for poor impedance matches, loss of power and, in many cases, poor frequency response.

It has been proposed to space successive discontinuities of this type by a quarter of a wavelength of the operating frequency. This suggestion is based on the fact that the reflections produced by any two adjacent such discontinuities will be exactly 180 degrees out of phase in the balance of the transmission line and will therefore cancel each other. While this arrangement does, indeed, give superior performance at the single frequency for which the spacing is a quarter of a wavelength, this improvement becomes less pronounced at frequencies further removed from this single frequency. These types of ultra-high frequency-transmission lines thus lose their most important attribute, i.e., broad frequency response.

It is an object of the present invention to increase the usable bandwidth of ultra-high-frequency transmission lines.

It is another object of the invention to reduce the losses and mismatches arising from the presence of necessary discontinuities in ultra-high-frequency transmission lines.

It is a more specific object of the invention to position multiple discontinuities in ultra-high-frequency transmission lines so as to produce optimum performance characteristics over any range of frequencies desired.

In accordance with the present invention, these and other objects are achieved in an electromagnetic wave transmission line by associating the actual and effective discontinuities of the line in successively higher orders of pairs and, furthermore, by spacing the two members of each pair of the several orders of pairs at a quarter of a wavelength of each of a like number of specific frequencies within a chosen band so as to provide optimum

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transmission characteristics over the entire band. To this end, all of the actual physical discontinuities are arranged in first order pairs and the members of each first order pair are spaced apart by a quarter wavelength of a first frequency within the band. Each of these first order pairs presents substantially no effective discontinuity to wave energy of the first frequency. Each of the first order pairs does, however, constitute a substantial effective discontinuity at all other frequencies. These effective discontinuities can be treated, for the purposes of the balance of the transmission line, as if they were physical discontinuities located at the center points of the several first order pairs.

In further accord with the present invention, the effective discontinuities constituted by the several first order pairs are arranged in second order pairs, and the members of each second order pair are spaced apart by a quarter wavelength of a second frequency within the band. That is, the center points of the first order pairs, and thus of the physical discontinuities, are separated by a quarter wavelength of the second frequency, which is within the desired band but which is different from the first frequency. Similarly, the effective discontinuities constituted by the several second order pairs are spaced apart by a quarter wavelength of a third frequency within the band to form third order pairs. Likewise the discontinuities constituted by the several third order pairs are spaced apart by a quarter wavelength of a fourth frequency within the band to form fourth order pairs. In fact, this pattern can be repeated any number of times to accommodate as large a number of frequencies as may be necessary fully to cover the desired band, provided only that the physical discontinuities are available in sufficient numbers.

It can be seen that the above pattern produces a transmission line structure which is substantially reflectionless for any number of specific frequencies within a band. In further accord with the invention, these specific frequencies are distributed across the band in such a manner as to produce minimum reflections at all intermediate frequencies within the band; that is, the maxima in the resulting reflections at any point within the band, for example, one of the extreme edges of the band, do not exceed the maxima in the reflections at any other point within the band, for example, near the center of the band. In this way the best compromise between bandwidth and impedance match is obtained over the entire band of interest.

These and other objects and features, the nature of the present invention and its various advantages, will appear more fully upon consideration of the accompanying drawing and of the following detailed description of the drawing.

In the drawing:

Fig. 1 is a cross-sectional view of a coaxial transmission line having a plurality of taps arranged in accordance with the present invention;

Fig. 2, given for the purposes of illustration, is a graphical and qualitative representation of the reflection coefficient versus frequency characteristic of the structure of Fig. 1;

Fig. 3 is a cut-away perspective view of a bead-supported coaxial transmission line arranged in accordance with the present invention; and

Figs. 4 through 6, given for the purposes of illustration, are graphical and qualitative representations of the reflection coefficient versus frequency characteristics of other transmission lines arranged in accordance with the present invention.

Referring more particularly to Fig. 1, there is shown a cross-sectional view of a primary coaxial transmission line 10 having an inner conductor 11 and an outer con-

ductor 12. Connected to coaxial line 10 are a plurality of secondary coaxial transmission lines numbered 13 through 20. Each of these secondary coaxial lines is also made up of a center conductor 21 and an outer conductor 22. The center conductors 21-1 through 21-8 of the secondary coaxial lines 13 through 20 are connected to the center conductor 11 of coaxial line 10. Similarly, the outer conductors 22-1 through 22-8 of secondary coaxial lines 13 through 20 are connected to the outer conductor 12 of coaxial line 10. In this way each of the secondary coaxial lines 13 through 20 provides a means for removing electromagnetic wave energy from the coaxial line 10. They are, therefore, termed "taps." It is to be understood, however, that the arrangement in Fig. 1 is only illustrative of one means for removing energy from an electromagnetic wave guiding structure. Probes, apertures, junctions or taps of any other configuration are equally suitable for this purpose and may be used in conjunction with hollow wave guiding structures without a center conductor, dielectric wave guiding structures, so-called "strip lines" or any other wave confining transmission structure. Coaxial taps on a coaxial transmission line have been illustrated in Fig. 1 merely to exemplify the manner in which the principles of the invention may be applied to the many other possible structures.

In accordance with the present invention, the taps formed by the secondary coaxial transmission lines 13 through 20 are arranged so as to produce minimum reflections over a desired frequency band. Thus, coaxial taps 13 and 14, 15 and 17, 16 and 18, 19 and 20 are arranged in first order pairs and the members of each first order pair are spaced apart by a quarter wavelength of one frequency (f_1) within the desired passband. These taps are, at the same time, so distributed along the length of the line 10 that the midpoint between the two members 13 and 14 of one first order pair and the midpoint between the two members 15 and 17 of another first order pair themselves constitute a second order pair spaced apart a quarter wavelength of another frequency (f_2) within the desired passband. Likewise, the first order pair comprising coaxial taps 16 and 18 and the first order pair comprising coaxial taps 19 and 20 are so arranged that their midpoints constitute a second order pair spaced apart by a quarter wavelength of the same frequency f_2 as the other second order pair. Furthermore, these two second order pairs are so located that their midpoints are spaced apart by a quarter wavelength of yet another frequency within the band (f_3) to form a third order pair. While only eight taps are illustrated in Fig. 1, it is clear that the pattern could be repeated for 16 taps, 32 taps, 64 taps, or any higher power of two. Thus, the present invention contemplates the arrangement of 2^n discontinuities in a wave transmission line where n is any integer greater than one.

Each of the coaxial taps of Fig. 1 presents a discrete discontinuity to an applied electromagnetic wave. If the reflection coefficient of each of these discontinuities is represented by ρ and if two of these discontinuities are located at distance $\pm d_1$ from a reference point, then the magnitude of the reflection coefficient of the first order pair thus formed can be represented by

$$\rho_1 = \left| \rho e^{2\gamma(-d_1)} + \rho e^{2\gamma(+d_1)} \right| \quad (1)$$

where

$\gamma = \alpha + j\beta$ = the propagation constant of the main transmission line,

α = the attenuation constant of the transmission line,

β = the phase constant of the transmission line, and

e = the base of the natural logarithms

If it is assumed that the attenuation constant α of the transmission line is small compared to the phase con-

stant β , true for high-frequency-transmission lines, then Equation 1 reduces to

$$\rho_1 \approx 2\rho \cos 2\beta d_1 \quad (2)$$

Proceeding in the manner shown in Fig. 1, two of these first order pairs are associated in a second order pair and the members of the second order pair are spaced at distances $\pm d_2$ from a reference point. In this case the reflection coefficient of this second order pair is

$$\begin{aligned} \rho_2 &= 2\rho_1 \cos 2\beta d_1 \\ &= 4\rho \cos 2\beta d_1 \cos 2\beta d_2 \end{aligned} \quad (3)$$

Further associations in yet higher order pairs lead to the following general representation of the reflection coefficient:

$$\rho_n = 2^n \rho \cos 2\beta d_1 \cos 2\beta d_2 \dots \cos 2\beta d_m \dots \cos 2\beta d_n \quad (4)$$

wherein n represents the order of the highest order pair and m is a subscript representing the number of the term.

Equation 4 can be further simplified if it is noted that $2d$ is a nearly quarter of a wavelength and hence $2\beta d$ is approximately equal to $\pi/2$. Under this condition,

$$\cos 2\beta d \approx \pi/2 - 2\beta d \quad (5)$$

and Equation 4 reduces to

$$\rho_n = 2^n \rho \left(\frac{\pi}{2} - 2\beta d_1 \right) \left(\frac{\pi}{2} - 2\beta d_2 \right) \dots \left(\frac{\pi}{2} - 2\beta d_m \right) \dots \left(\frac{\pi}{2} - 2\beta d_n \right) \quad (6)$$

It should be noted that ρ_n must go through zero at the frequencies for which any one of the spacings is exactly a quarter wavelength. For the purposes of the present invention, it is also desired that ρ_n have deviations from zero at the edges of the band of interest equal to the deviations at all maxima and minima therebetween. The solutions to Equation 6 which provide these equal deviations are known as the Tschebyscheff polynomials and have the following general form in the range $-1 \leq x \leq 1$

$$T_n(x) = \cos(n \cos^{-1} x) \quad (7)$$

Taking frequency as the independent variable and normalizing the frequency range extending from f_A to f_B (i.e., $f_A \leq f \leq f_B$) to the range of the Tschebyscheff polynomials require that

$$f = \frac{f_A + f_B}{2} + x \left[\frac{f_B - f_A}{2} \right]$$

and

$$x = \frac{2f - f_A - f_B}{f_B - f_A} \quad (8)$$

Substituting this value in the Tschebyscheff polynomial, there is obtained

$$\rho_n = \cos \left[n \cos^{-1} \left(\frac{2f - f_A - f_B}{f_B - f_A} \right) \right] \quad (9)$$

The roots occur when $\rho_n = 0$ or

$$\cos \left[n \cos^{-1} \left(\frac{2f - f_A - f_B}{f_B - f_A} \right) \right] = 0 \quad (10)$$

Solving for f gives

$$f = \frac{f_A + f_B}{2} + \frac{f_B - f_A}{2} \cos \left[(2m-1) \frac{\pi}{2n} \right] \quad (11)$$

where m is an integer between one and n and represents the order of the pair as shown in Fig. 1.

Now, as pointed out above, the distances d_m are actually each an eighth of a wavelength and hence equal to

$$\begin{aligned} d_m &= \frac{v/8}{f} \\ &= \frac{v/8}{\frac{f_A + f_B}{2} + \frac{f_B - f_A}{2} \cos \left[(2m-1) \frac{\pi}{2n} \right]} \end{aligned} \quad (12)$$

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where v is the velocity of propagation of a traveling wave along line 10. This distance is measured from a common reference point and may be represented by

$$x = \pm d_1 \pm d_2 \pm d_3 \dots \pm d_m \dots \pm d_n$$

The application of Equation 13 to the structure of Fig. 1 may be accomplished as follows. Starting at an arbitrary reference point 23 along the length of the coaxial transmission line, distance d_3

$$\left(\text{one-half } \frac{\gamma_3}{4}\right)$$

is measured off in both directions along the line to determine secondary reference points. From these secondary reference points the distance d_2

$$\left(\text{one-half } \frac{\gamma_2}{4}\right)$$

is measured off in both directions to determine tertiary reference points. From the tertiary reference points the distance d_1

$$\left(\text{one-half } \frac{\gamma_1}{4}\right)$$

is measured off in both directions to determine, in the example of Fig. 1, the actual physical location of the taps. The process could, however, be continued to determine fourth and higher order reference points and thus extend the number of taps accommodated to sixteen or more.

The advantage of the arrangements of the present invention can be more readily understood by a consideration of Fig. 2, which is a graphical representation of the reflection coefficient versus frequency characteristic of two multi-tapped coaxial lines. The solid curve 24 represents the characteristic of the configuration shown in Fig. 1. It will be first noted that the reflection coefficient is zero at three discrete frequencies, f_1 , f_2 and f_3 , corresponding to the three frequencies for which the spacings are exactly a quarter of a wavelength. Furthermore, the maximum deviation from zero over the entire frequency range f_A to f_B does not exceed $|\rho_{\max}|$ where $|\rho_{\max}| = |\rho_{\min}|$. The advantages of this arrangement are clear when it is compared to dashed curve 25.

Dashed curve 25 represents the reflection coefficient versus frequency characteristic of a multi-tapped coaxial line similar to that of Fig. 1, but where all of the spacings are equal to a quarter of a wavelength of a single frequency f_2 . It can be seen that while the response is improved near and at frequency f_2 , at the edges of the band (at frequencies f_A and f_B), the response has substantially deteriorated compared to curve 24. In accordance with the present invention then, the response of the transmission line is optimized over the band f_A to f_B .

It is apparent that any other form of energy removing structure which presents a discontinuity can be treated similarly to the taps of Fig. 1. Thus, apertures, probes, loops, junctions and other waveguide structures also represent discontinuities which can be broadbanded in the manner taught with respect to Fig. 1. Indeed, the method can be extended to any plurality of discrete, reflection-producing, substantially like discontinuities appearing in an electromagnetic wave guiding transmission line. Another example of the application of the principles of the invention is illustrated in Fig. 3.

In Fig. 3 there is shown a perspective view of a section of coaxial line 30 having an outer conductor 31 and an inner conductor 32. In order to support inner conductor 32 within outer conductor 31, a plurality of dielectric spacers or beads 33 through 40 are inserted in coaxial line 30. Each of the dielectric spacers 33 through 40 has a peripheral contour matching the inner surface of outer conductor 31 and each has a centrally located hole through which center conductor 32 may pass. While dielectric spacers 33 through 40 are shown as disc-shaped

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elements, they may in fact take any shape which will provide support for center conductor 32 and may be of any material with sufficient rigidity to give such support.

In accordance with the present invention, the spacers 33 through 40 are positioned longitudinally along coaxial line 30 so as to produce minimum reflections over a wide range of frequencies. Thus spacers 33 and 34, 35 and 37, 36 and 38, 39 and 40 are associated to form first order pairs the members of which are spaced apart by a quarter of a wavelength of a first frequency f_1 . Similarly, the pair comprising spacers 33 and 34 and the pair comprising spacers 35 and 37 are associated in a second order pair with their center points spaced apart a quarter wavelength of a second frequency f_2 . The pair comprising spacers 36 and 38 and the pair comprising spacers 39 and 40 are also associated in another second order pair with their center points spaced apart by a quarter wavelength of the same frequency f_2 . The second order pairs thus formed are themselves spaced apart by a quarter wavelength of a third frequency f_3 . That is, the center points of the second order pairs are spaced to form a third order pair with the desired distance between them. As with the taps of Fig. 1, the number of spacers which might be accommodated by the principles of the invention is not limited to eight as illustrated. Any 2^n spacers may be accommodated by following the spacing procedure set forth above.

In Figs. 4 through 6 there are shown the reflection coefficient versus frequency characteristics of transmission lines similar to those shown in Figs. 1 and 3 but with the number of discontinuities extended to 16, 32 and 64. Thus, in Fig. 4 there is shown the characteristic of a structure having sixteen discrete, reflection-producing discontinuities, such as taps or spacers. It can be seen that the reflection coefficient is zero at four discrete frequencies within the band and that the maximum deviation from zero is the same at the edges of the band as at the center. Similar characteristics shown in Figs. 5 and 6 have five and six zero crossovers, respectively, and also have the same maximum deviation from zero at the edges of the band and at any point within it. It should also be noted that, for the same passband, the maximum deviation from zero becomes progressively less as the number of discontinuities accommodated is increased. This property is important for structures such as the bead-supported coaxial line illustrated in Fig. 3 where a large number of spacers are required to support the center conductor of a coaxial line of any substantial length.

It is to be understood that the above-described arrangements are merely illustrative of the numerous and varied other arrangements which could represent applications of the principles of the invention. Such other arrangements may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A communication system for uniformly transmitting electromagnetic wave energy in a frequency range between a lower and an upper frequency limit, which communication system comprises a transmission line and 2^n discrete, substantially like discontinuities in said transmission line, said discontinuities being spaced in the relation

$$x = \pm d_1 \pm d_2 \pm d_3 \pm \dots \pm d_n$$

where x is the distance to each of said discontinuities measured from a fixed reference point along the length of said transmission line, n is any integer greater than one and where

$$d_m = \frac{v/8}{\frac{f_A + f_B}{2} + \frac{f_B - f_A}{2} \cos \left[\frac{(2m-1)\pi}{2n} \right]}$$

v being the velocity of propagation of a traveling wave along said line f_A and f_B being said lower and upper

frequency limits, respectively, and m being an integer successively valued one through n .

2. A communication system according to claim 1 in which each of said discontinuities comprises means for removing a portion of the electromagnetic wave energy traversing said transmission line.

3. A communication system according to claim 1 in which said transmission line comprises cylindrical outer and inner conductors and in which said discontinuities comprise means for supporting said inner conductor in coaxial relationship with said outer conductor.

4. An electromagnetic wave transmission line including a plurality of discrete discontinuities, said discontinuities being grouped in first order pairs, the members of said first order pairs being spaced apart by an electrical quarter wavelength of a first frequency, said first order pairs being grouped in second order pairs, the members of said second order pairs being spaced apart by an electrical quarter wavelength of a second frequency, said second order pairs being grouped in third order pairs, the members of said third order pairs being spaced apart by an electrical quarter wavelength of a third frequency.

5. An ultra-high-frequency transmission line having 2^n discrete, substantially like, reflection-producing discontinuities, where n is any integer greater than one, said discontinuities being arranged in pairs of successively higher orders corresponding to successive powers of 2, the members of the several pairs of each of said orders being spaced apart by an electrical quarter wavelength of a discrete frequency within a band of frequencies, said discrete frequencies differing from order to order.

6. A transmission system for a selected band of frequencies, which system comprises an electromagnetic wave guiding structure having 2^n discrete discontinuities included therein, said discontinuities being spaced along the length of said wave guiding structure according to the formula

$$x = \pm d_1 \pm d_2 \pm \dots \pm d_m \pm \dots \pm d_n$$

where x is the distance to each of said discontinuities

measured from a fixed reference point along the length of said wave guiding structure, d_m is an eighth of a wavelength of any one of n discrete frequencies with said band, and n is any integer greater than one.

7. The transmission system according to claim 6 in which said distances are equal to an eighth of an electrical wavelength of the frequencies having the following value

$$f_m = \frac{f_A + f_B}{2} + \frac{f_B - f_A}{2} \cos \left[\frac{(2m-1)\pi}{2n} \right]$$

where f_m is any one of said n discrete frequencies, and f_A and f_B are the lower and upper frequency limits, respectively, of said selected band of frequencies.

8. An electromagnetic wave distributing system for a selected band of frequencies, which system comprises a primary electromagnetic wave guiding structure and a plurality of secondary wave guiding structure, said secondary structures being coupled to said primary structure at discrete points along its length, said points being spaced in the relation

$$x = \pm d_1 \pm d_2 \pm d_3 \pm \dots \pm d_n$$

where x is the distance to each of said points measured from a fixed reference point along the length of said primary wave guiding structure, n is any integer greater than one, and where

$$d_m = \frac{v/8}{\frac{f_A + f_B}{2} + \frac{f_B - f_A}{2} \cos \left[\frac{(2m-1)\pi}{2n} \right]}$$

v being the velocity of propagation of electromagnetic waves along said primary structure, f_A and f_B being the lower and upper frequency limits, respectively, of said selected band, and m being an integer successively valued one through n .

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