

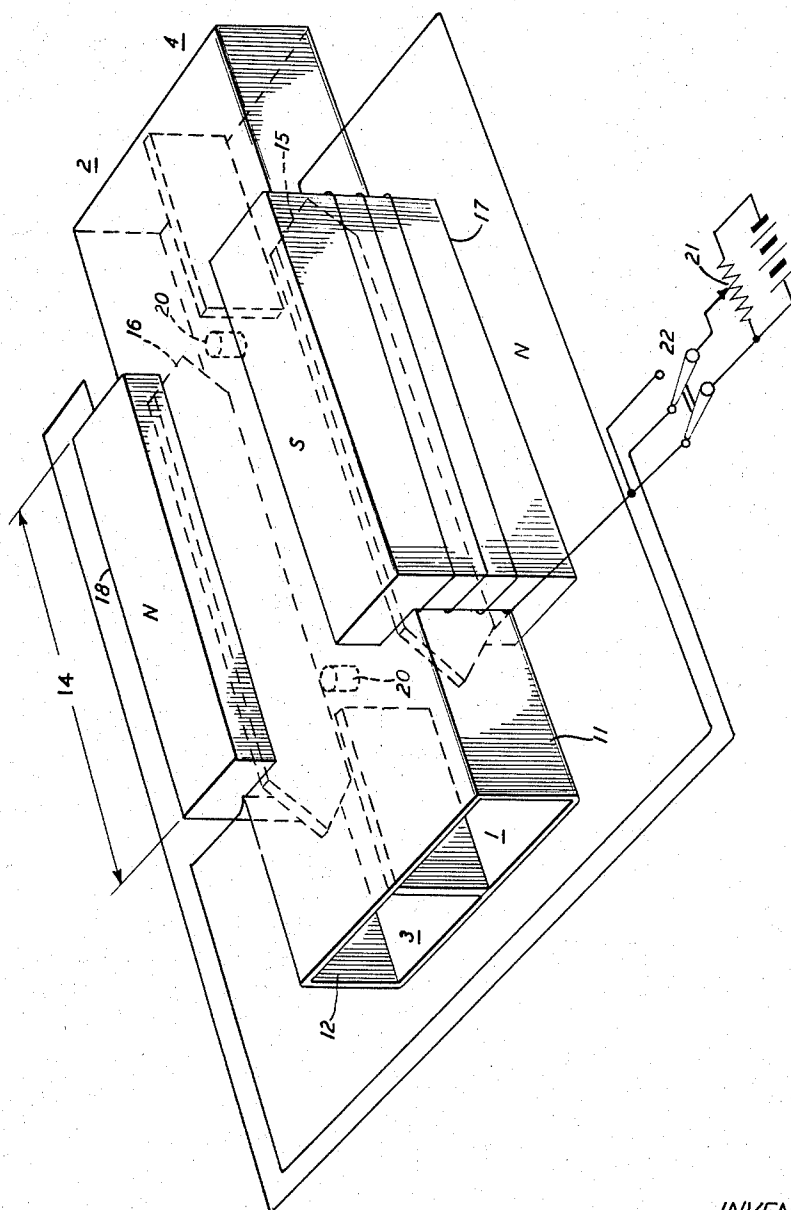
July 7, 1959

W. J. CROWE

2,894,216

NON-RECIPROCAL WAVE TRANSMISSION

Filed June 11, 1956



INVENTOR
W. J. CROWE
BY *Ray M. Porter, Jr.*

ATTORNEY

1

2,894,216

NON-RECIPROCAL WAVE TRANSMISSION

William J. Crowe, Hanover Township, Morris County, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application June 11, 1956, Serial No. 590,555

10 Claims. (Cl. 333—7)

This invention relates to very high frequency or microwave electrical transmission systems, and more particularly, to coupled line systems for dividing or completely transferring electromagnetic wave energy, such as directional couplers.

It is a principal object of this invention to provide complete non-reciprocal energy transfer between two coupled electromagnetic wave transmission lines, i.e., circulator action.

It is an additional object of this invention to provide a non-reciprocal, electrically adjustable division of electromagnetic wave energy between two transmission lines.

It is well known in the art that two hollow pipe electromagnetic wave transmission lines may be coupled by virtue of a slot in their common narrow wall so as to provide a reciprocal transfer or division of wave energy therebetween. This is accomplished by virtue of the phase relationships of the modes of energy propagated along the guides in the region of the coupling slot. Specifically, the dominant mode wave entering the principal guide in the forward direction will excite both dominant mode and TE_{20} mode components in that section of the wave guide having the coupling slot. In this section, by virtue of the slot, the principal guide and the coupled auxiliary guide actually form a single double-width guide whose wide dimension is equal to the sum of the wide dimensions of the principal and auxiliary guides. In this region the excited dominant, and TE_{20} mode components travel at respectively different phase velocities. As is well known in the art, the dominant mode component has a smaller velocity than the TE_{20} mode. At the beginning of the coupling slot region the dominant mode component is in phase with the TE_{20} mode component on that side of the double-width wave guide equivalent to the principal wave guide. On the opposite side of the double guide coinciding with the auxiliary wave guide the TE_{20} mode component is 180 degrees out of phase with the dominant mode component. Since the phase constants of the two mode components are different, the phase relationship between the two modes will progressively change as the modes are propagated along the double guide whose length is defined by the coupling slot. If the coupler is of the type that provides complete power transfer, the phase relationship of the two modes at the end of the coupling region, that is at the end of the coupling slot, will be exactly the reverse of the phase relationship at the beginning of the coupling slot. Specifically, the dominant and TE_{20} modes will be out of phase in the principal guide half of the double guide and in phase in the auxiliary guide half of the double guide. By providing a suitable reactance at each end of the coupling slot the dominant mode is matched into the principal and auxiliary guides. The TE_{20} mode, which is naturally well matched to the principal and auxiliary guides, due to its having an electric-field null at the center of the double guide, is unaffected by the reactances. Thus, at the end of the coupling region, the in phase portions of the two modes will excite a dominant mode in the auxiliary guide while no energy will propagate down the principal guide. In this way, we have

2

a complete transfer of wave energy in the forward direction from the principal to the auxiliary guide. Now a dominant mode traveling in the reverse direction along the auxiliary guide towards the coupling region will undergo precisely the same procedure and will be coupled completely into the principal guide. This, of course, defines a reciprocal directional coupler providing complete power transfer. If some type of power division other than complete transfer is desired, this may be obtained by changing the length of the coupling slot so that the phase relationships of the two modes will add to give either equal power division between the principal and auxiliary guides or any other division that is desired. In all cases, however, the coupling will be reciprocal as described above.

In accordance with the invention a directional coupler of the type above described is made non-reciprocal, that is, energy propagated in the forward direction along the principal guide will be coupled into the auxiliary guide but energy traveling in the reverse direction along the auxiliary guide will not be coupled into the principal guide but rather will continue along the auxiliary guide. Such would be the case where complete power transfer is involved. Where a particular division of energy is desired, the division would also be non-reciprocal. This is accomplished in the invention by symmetrically loading a double-width wave guide formed by principal and auxiliary guides in the region of a coupling slot with two elements of gyromagnetic material in a special way hereinafter to be described. The effect of this loading is two-fold. Firstly, it maintains the respective types of symmetry of the two modes of propagation so that they will be matched from the coupling region into the principal and auxiliary wave guides in the manner described above. Secondly, the loading provides a special phase relationship between the two modes which relationship is different for different directions of propagation. Specifically, in the forward direction of propagation, the phase constants of the two modes excited by energy in the principal guide will differ by an amount which will result in a phase relationship at the end of the coupling interval that results in the two modes being in phase in the auxiliary half of the double wave guide and 180 degrees out of phase in the principal guide, thus resulting in complete power transfer from the principal to the auxiliary guide. In the reverse direction of propagation, however, energy in the auxiliary guide will excite two modes which have different phase constants than they had in the forward direction due to the non-reciprocal gyromagnetic loading. It is clear, that if the difference between the phase constants in the reverse direction is twice that of the difference between the phase constants in the forward direction the phase relationship of the two modes at the end of the coupling interval, while traveling in the reverse direction, will be exactly opposite from what it was in the forward direction. Specifically, the two modes will be in phase in the auxiliary guide and exactly out of phase in the principal guide. Thus, non-reciprocal coupling is achieved. It is clear that by appropriately proportioning the dimensions of the gyromagnetic elements and the magnetic fields biasing them, any particular phase constant relationship may be achieved and consequently, any desired division of energy between the guides may also be achieved in a non-reciprocal fashion.

A special feature of the invention resides in the fact that the wave guide is symmetrically loaded with two gyromagnetic elements each of which is on an opposite side of the double-width guide in the coupling region and which are magnetically biased in opposite senses. Due to this opposite bias, the wave propagation is non-reciprocal. Due to the symmetrical disposition of the gyromagnetic elements and also their respectively opposite biasing, the

modes of propagation in the loaded wave guide maintain their respective types of symmetry about the longitudinal axis of the double width guide even though loading the guide results in distorting the modes from the pure TE_{10} and TE_{20} form that they have in an unloaded guide. Accordingly, the TE_{10} -like and TE_{20} -like modes are matched into the principal and auxiliary wave guides in the manner above-described even though their field patterns are somewhat different from the pure TE_{10} and TE_{20} modes that exist in an unloaded guide.

The nature of the present invention, its various objects, features and advantages will appear more fully upon consideration of the illustrative embodiment shown in the accompanying drawing and the following detailed description thereof.

The drawing represents a perspective view of a directional coupler loaded with gyromagnetic material, in accordance with the invention, so as to provide total non-reciprocal power transfer, i.e., circulator action, and is presented by way of example, for purposes of illustration. Referring specifically to the drawing, a principal metallic, hollow, rectangular wave guide 11 having terminals 1 and 4, is coupled to an auxiliary and similar wave guide 12, having terminals 2 and 3, along their common narrow wall. Coupling between guides 11 and 12 occurs by virtue of slot 13, which is formed by removing an entire rectangular section of the common wall of length L such that from the beginning of the coupling region 14 to the end thereof, no wall exists between guides 11 and 12. Guides 11 and 12 each have wide dimensioned walls of the same dimension greater than one-half wavelength of the operating frequency so that dominant mode energy may be propagated therein. However, the widths of these guides are also proportioned such that their combined widths forming the wide dimension of the double width guide in coupling region 14, will support both the TE_{10} -like and TE_{20} -like modes but will cut off all higher order modes. Thus the combined widths of guides 11 and 12 will be some value between one and one and one-half wavelengths of the operating frequency. Disposed longitudinally near, and parallel to each of the outside narrow walls of guides 11 and 12 is a slab of gyromagnetic material 15 and 16 respectively. These slabs have similar shapes and may extend substantially the entire length of coupling region 14. They may occupy a substantial portion of the height of the wave guides. However, the factors controlling the requirements of the slab dimensions are the phase constants required in the operation of the embodiment and these are discussed, hereinafter, in detail. Slabs 15 and 16 are disposed symmetrically in the double width guide, i.e., they are equidistant from the coupling slot in region 14. Also they are disposed closer to the narrow walls of their respective guides 11 and 12 than they are to the coupling slot. Slabs 15 and 16 may extend beyond the limits of region 14 in a tapered fashion well known in the art so as to minimize reflections therefrom. Gyromagnetic slabs 15 and 16 may be composed, for example, of ferrite material which, as is well known in the art, exhibits a non-reciprocal permeability characteristic to wave energy propagated there-through when appropriately magnetically biased. Disposed about a portion of wave guide 11 coincident with the position of ferrite 15 is a means for magnetically biasing the ferrite, such as electromagnet 17, having its south pole on the top of guide 11 coextensive with the length of slab 15 and its north pole on the bottom of guide 11 coextensive with the bottom length of ferrite 15. Accordingly, electromagnet 17 provides a magnetic bias to ferrite 15. This bias is perpendicular to the longitudinal axis of wave guide 11 and to the direction of wave energy propagated therein. An electromagnet 18 is disposed in similar fashion about guide 12 and in similar relation to ferrite 16 except that the pole pieces of magnet 18 are the reverse of magnet 17. Consequently, ferrite 15 is subject to a magnetic bias having a sense opposite to the

magnetic bias afforded ferrite 16. In coupling region 14 there is disposed, at each end of the slot in the common wall, a small reactive post 20 fixed in the wide wall of the double-width wave guide on the longitudinal centerline thereof and extending a short distance into the coupling region parallel to the common wall. The function of the reactive posts is to match the TE_{10} -like mode excited in coupling region 14 into guides 11 and 12.

Consider now the operation of the embodiment depicted in the drawing. A dominant mode wave entering principal guide 11 in the forward direction at terminal 1 excite both a TE_{10} -like mode and a TE_{20} -like mode across guides 11 and 12 in region 14. Each of these modes will have a particular phase constant determined by the dimensions of ferrite slabs 15 and 16, the type of ferrite the slabs are composed of, and also by the strength of the magnetic field biasing the slabs. Because of the oppositely sensed biases respectively afforded the ferrite slabs, both modes will be symmetric across the combined width of guides 11 and 12 and, more particularly, transversely symmetric about the longitudinal plane defined by the coupling slot. Specifically, the TE_{10} -like mode will have even symmetry about the plane while the TE_{20} -like mode will have odd symmetry thereabout. It may be seen, therefore, that at the beginning of coupling region 14 the TE_{10} -like and TE_{20} -like modes will be in phase in guide 11 and out of phase in guide 12. As is well known in the art, the phase velocities for the two modes are unequal with that of the dominant mode being the smaller. Consequently, the phase relationship of the two modes will change as the modes propagate along region 14 in the forward direction. The length L of coupling region 14 is fixed so that the phase relationship of the modes at the end of distance L is exactly 180 degrees different from what it was at the beginning of the coupling region; that is, $(\beta_{FE} - \beta_{FO})L = (2n - 1)\pi$, where β_{FE} is the phase constant of the TE_{10} -like or even symmetry mode in the forward direction, β_{FO} the phase constant for the TE_{20} -like or odd symmetry mode in the forward direction, and n is an integer. Consequently, at the end of coupling distance L , the two modes are out of phase in principal guide 11 but in phase in auxiliary guide 12. The reactive post 20 serves to match the even mode at the end of the coupling interval into guides 11 and 12. Since the two modes will be out of phase in guide 11, no energy will propagate therein. However, in guide 12 with the modes in phase, all the energy which initially entered guide 11 at terminal 1 will propagate down guide 12 to terminal 2. Consider, now, energy propagated in the opposite or reverse direction, that is, energy entering guide 12 at terminal 2. On reaching coupling region 14 the dominant mode energy in guide 12 will excite again both the odd and even symmetric modes across the combined width of guides 11 and 12. However, the phase constants of each of the modes in this reverse direction of propagation are different from what they were in the forward direction of propagation due to the non-reciprocal properties of ferrite slabs 15 and 16. Furthermore, not only are the phase constants different for the forward and reverse directions, but the difference between the mode phase constants for the reverse direction is also different from the difference between the mode phase constants for the forward direction. To have complete and non-reciprocal transfer of power, the energy entering guide 12 at terminal 2 must exit the coupler from guide 12 at terminal 3, i.e., the two modes must be in phase at terminal 3 and out of phase at terminal 1. This can only occur if the difference between mode phase constants in the reverse direction results in a 360-degree relative phase shift (or an integral multiple thereof) between the two modes along coupling length L . When this occurs, the phase relationship of the two modes at the end of the coupling interval is precisely the same as it was at the beginning of the coupling interval and thus the energy will remain in guide 12. Specifically, this phase relation-

ship can be defined as $(\beta_{RE} - \beta_{RO})L = 2\pi n$ where R means reverse direction of propagation. Thus, with a given coupling device having a given aperture of length L, complete and non-reciprocal power transfer results by virtue of the properly proportioned ferrite slabs and their biasing fields. The above-described ferrite loading provides a difference between the phase constants for one direction of propagation that is equal to twice the difference between phase constants for the opposite direction of propagation; that is, $(\beta_{RE} - \beta_{RO}) = 2(\beta_{FE} - \beta_{FO})$. The phase constant relationship may readily be varied to change the ratio of power transfer by adjusting potentiometer 21 so as to change the strength of the magnetic fields biasing ferrites 15 and 16.

The above description of the operation of the embodiment depicted in the drawing was confined to energy entering but two terminals of the coupler, namely, terminals 1 and 2. For reasons of symmetry, it is clear that the operation for energy entering terminal 3 will be precisely the same as that for energy entering terminal 1, and terminal 4 energy will behave as did terminal 2. It may be seen, therefore, that when complete power transfer is provided in the manner above described, circulator action is achieved, that is, energy entering any given numbered terminal will be coupled to the next succeeding higher numbered terminal. Also, by reversing the polarities of biasing magnets 17 and 18 by means of switch 21 and thereby reversing the senses of the magnetic biases applied to ferrites 15 and 16 the circulator action is reversed. Specifically, energy entering any given numbered terminal will be coupled to the next succeeding lower numbered terminal.

In all cases, it is understood that the above-described arrangement is simply illustrative of one of many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with said principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A non-reciprocal directional coupler for electromagnetic waves comprising two hollow rectangular metallic wave guides disposed parallel to each other and extending in a common direction, said guides having a length of one of their respective narrow walls in common, a coupling region of given length in said common wall comprising a coupling slot extending in said common direction, said two guides thereby forming a single wave guiding structure along said given length whose longitudinal axis lies in the plane of said common wall, said single guide supportive of both a TE_{10} -like and TE_{20} -like mode of wave energy propagation, non-reciprocal means comprising two ferrite slabs disposed along said given length and on respectively opposite sides of said longitudinal axis and equidistant therefrom, and means for magnetically biasing each of said ferrite slabs in a sense opposite to each other and in a direction perpendicular to said longitudinal axis, said ferrite slabs physically proportioned relative to a given strength of said magnetic bias to provide a phase constant difference between said two modes for a first direction of propagation equal to twice the phase constant difference between said modes for the reverse direction of propagation.

2. A combination, as recited in claim 1, wherein said single wave guiding structure is proportioned to support said TE_{10} and TE_{20} modes to the exclusion of all other modes of wave propagation.

3. A combination, as recited in claim 1, wherein said magnetic biasing means is variable in magnetic strength.

4. A combination, as recited in claim 1, including reactive elements disposed in said coupling slot for matching said TE_{10} -like mode from said single wave guiding structure into said two metallic wave guides.

5. In combination, first and second hollow metallic wave guides disposed parallel to each other and contiguous

to each other along a common length of their respective walls, means for coupling electromagnetic wave energy between said first and second guides, said first and second guides jointly supportive of two different modes of wave energy propagation in the region of said coupling means, and means for providing a difference between the phase constants of said two modes for a given direction of propagation that is different from the difference between phase constants for said two modes in the reverse direction of propagation.

6. A combination as recited in claim 5 wherein said last named means provides a difference between said phase constants of said two modes for a given direction of propagation equal to twice the difference between said phase constants for said two modes in the reverse direction of propagation.

7. A circulator for electromagnetic wave energy comprising two hollow pipe metallic wave guides disposed parallel to each other and extending in a common direction, said guides having a section of one of their respective walls in common, a coupling slot of length L in said common wall extending in said common direction, said two guides thereby forming a single wave guide structure over said length L, said single guide supportive of two different modes of wave energy propagation, said modes having transverse electric field configurations that are respectively evenly and oddly symmetric about said coupling slot, means for introducing a relative phase shift between said modes over said length L equal to $2\pi n$ in a given direction of propagation, where n is an integer, and for introducing a relative phase shift between said modes over said length L equal to $(2n-1)\pi$ in a reverse direction of propagation, said means including means for maintaining said even and odd symmetry of said respective modes about said coupling slot.

8. A non-reciprocal directional coupler for electromagnetic wave energy comprising two rectangular hollow pipe metallic wave guides disposed parallel to each other and extending in a common direction, said guides having the same transverse cross sectional dimensions with the wide dimensions equal to some value between $\lambda/2$ and $3\lambda/4$ inclusive, where λ is the wavelength of the operating frequency, said guides having a length of one of their respective narrow walls in common, a coupling region of given length in said common wall comprising a coupling slot extending in said common direction, and non-reciprocal means comprising two oppositely magnetized ferrite elements disposed parallel to said slot on respectively opposite sides thereof and equidistant therefrom.

9. A nonreciprocal electromagnetic wave transmission device comprising first and second electromagnetic wave transmission lines mutually coupled over a common length and adapted to support along said length first and second distinct electromagnetic modes of wave propagation having different phase constants, and means for providing a difference between the phase constants of said first and second modes for a given direction of propagation through said device along said length that is different from the difference between phase constants for said first and second modes in the reverse direction of propagation through said device along said length.

10. A combination as recited in claim 9 wherein said last named means provides a difference between the phase constants of said first and second modes for a given direction of propagation which is equal to twice the difference between the phase constants of said first and second modes in the reverse direction of propagation.

References Cited in the file of this patent

UNITED STATES PATENTS

2,739,287	Riblet	Mar. 20, 1956
2,848,688	Fraser	Aug. 19, 1958

(Other references on following page)

OTHER REFERENCES

Kales et al.: "A Nonreciprocal Microwave Component,"
Journal of Applied Physics, vol. 24, No. 6, June 1953,
pages 816-17.

Lax et al.: "Ferrite Phase Shifters in Rectangular Wave-

guide," Journal of Applied Physics, vol. 25, No. 11,
November 1954, pages 1413-21.

Fox et al.: Bell System Technical Journal, vol. 34,
No. 1, January 1955, pp. 42-61 and 103. (Copy in
Scientific Library.)