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2,929,034

MAGNETIC TRANSMISSION SYSTEMS

Filed April 29, 1953

2 Sheets-Sheet 1

FIG. 1

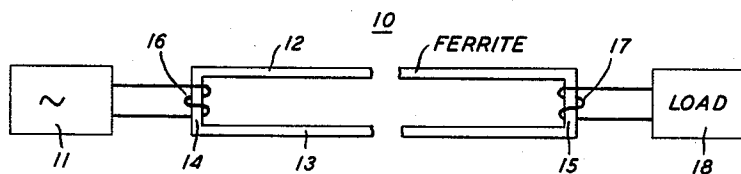


FIG. 2

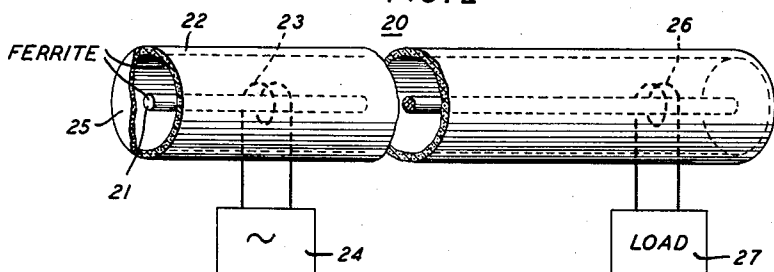


FIG. 3

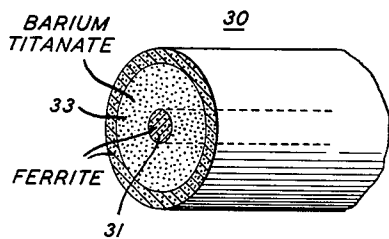


FIG. 4

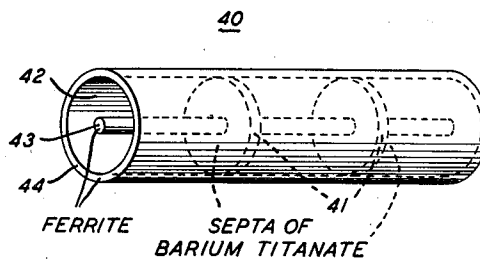


FIG. 5

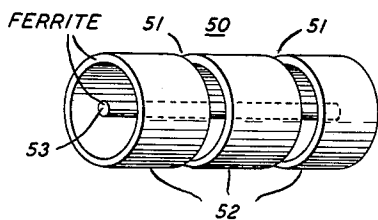
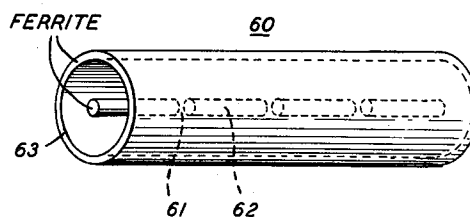


FIG. 6



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FIG. 7

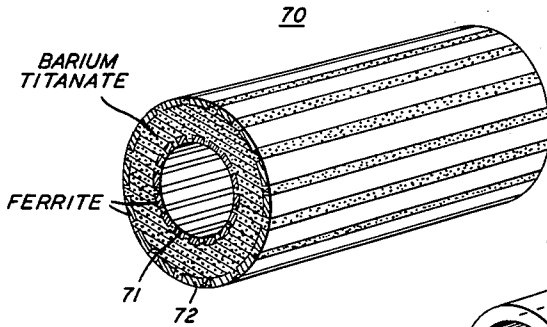


FIG. 8

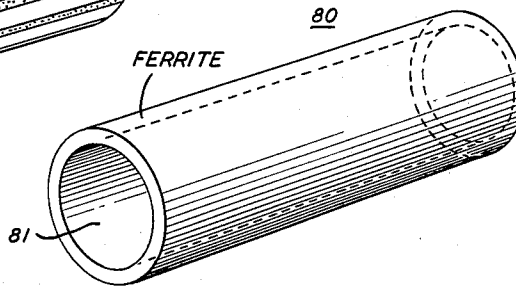


FIG. 9

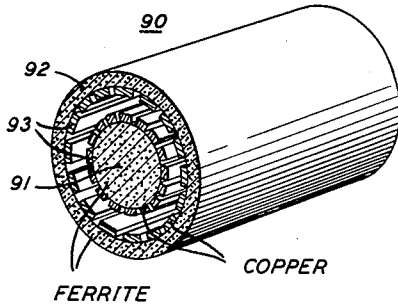


FIG. 10

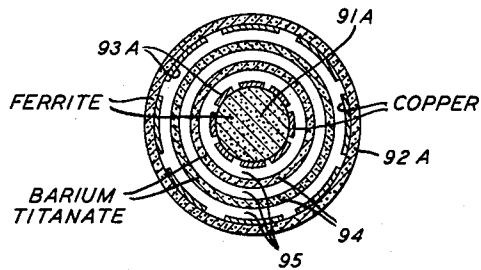


FIG. 11

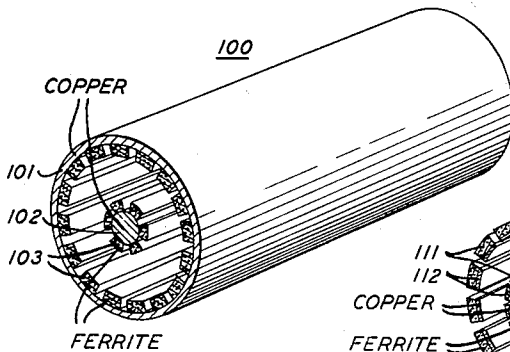
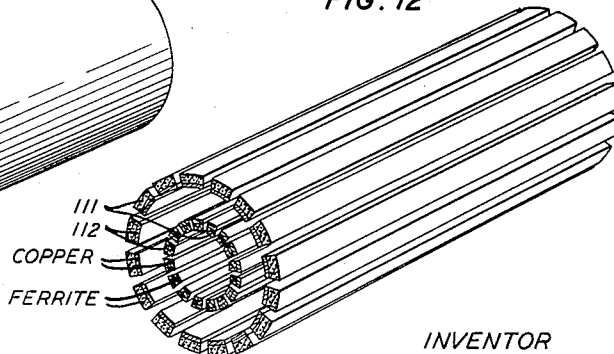


FIG. 12



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MAGNETIC TRANSMISSION SYSTEMS

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11 Claims. (Cl. 333—84)

This invention relates to methods of and apparatus for the transmission of electrical effects by electromagnetic waves. Such apparatus includes transmission lines, delay lines, and resonators.

Hitherto, in the transmission of electromagnetic waves it has been the usual practice to guide or confine the electromagnetic wave in a desired path by the use of electrically conducting boundaries. Typical of apparatus of this kind are conventional parallel and coaxial pair transmission lines, and hollow pipes or wave guides. Alternatively, it has sometimes been the practice to confine the electromagnetic wave to a desired path by means of a solid guide of material having a dielectric constant greater than that of the surrounding medium. All such prior art devices are characterized in that they comprise a dielectric medium (for example, free space) having enclosing boundaries defining discontinuities in electrical properties for confining the electric field of the electromagnetic wave.

A feature of the present invention is the guiding of an electromagnetic wave by operating primarily on the magnetic field of the wave. To this end, the present invention provides wave guiding means which includes a propagation medium enclosed by boundaries of high magnetic permeability defining discontinuities in magnetic properties for confining the magnetic field of the wave to the propagation medium.

In accordance with these principles there is provided a plurality of novel transmission lines for the guiding of electromagnetic wave energy. Characteristic of these transmission lines is the use of a dielectric propagation medium which is enclosed by boundaries having a low electrical conductivity but high magnetic permeability. In this way, the guiding of the wave energy is achieved primarily by elements having a high magnetic susceptibility rather than a high electrical admittance. It will be convenient in the specification to characterize as "magnetic" an element of a material having a relatively low electrical conductivity but a relatively high magnetic permeability. In general, the operation will be enhanced the higher the permeability and the lower the conductivity.

Typical of such materials are the ferrites, which are relatively homogeneous crystalline compounds comprising the reaction product of iron oxide and at least one other metallic oxide and having the general chemical formula of $XOFe_2O_3$. Such materials have initial permeabilities of several thousands. In particular, for operation at the lower radio frequencies, manganese zinc ferrites such as $Mn_{0.5}Zn_{0.5}Fe_2O_4$ will be advantageous while for operation at the higher radio frequencies, nickel zinc ferrites such as $Ni_{0.3}Zn_{0.7}Fe_2O_4$ will be advantageous.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings, in which:

Fig. 1 shows schematically a transmission system in which electromagnetic waves are guided from an input

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source to output utilization apparatus by means of a parallel pair of magnetic lines in accordance with an illustrative embodiment of the invention;

Fig. 2 shows schematically as an alternative embodiment a transmission system in which electromagnetic waves are guided by a magnetic coaxial line;

Figs. 3, 4, 5, 6 and 7 illustrate schematically various expedients for varying the transmission characteristics of a coaxial line of the kind shown in Fig. 2;

Fig. 8 shows schematically, as another embodiment a hollow magnetic wave guide; and

Figs. 9 through 12 show schematically hybrid wave guides suitable for independent transmission of waves of different modes.

Referring now more specifically to the drawings, in the system 10 shown in Fig. 1 an input source 11 supplies the signal energy which is to be transmitted to utilization apparatus 18 over a wave guiding path which is defined by a parallel pair 12 and 13 of "magnetic conductors," i.e., lines composed of material having a high magnetic permeability and a low electrical conductivity, typical of which are the ferrites described above.

The physical structure of this parallel pair may have any of the physical configurations characteristic of conventional parallel pair transmission lines of electrical conductors. Various arrangements can be provided for initially launching the signal wave for travel along the transmission path defined by the parallel pair of magnetic conductors and for eventually abstracting the wave from the transmission path for utilization. In the embodiment depicted, the parallel pair 12 and 13 are shunted at the input and output ends by magnetic elements 14 and 15, respectively, about each of which are wound turns of an electrical conductor for forming the input and output transducers 16 and 17, respectively. The input transducer 16 is connected across the source 11 of input signal power while the output transducer 17 is connected across the load 18 to which the signal power is to be supplied.

In operation, the signal power from the source 11 is supplied by means of the input transducer 16 to the input end of the transmission path defined by the magnetic conductors 12 and 13 for propagation therealong to the output end where it is abstracted by the output transducer 17 and supplied to the load 18. Each of the various wave guiding means disclosed hereinafter can similarly serve as a transmission path between a signal source and a load.

In Fig. 2, there is shown a system 20 in which a coaxial pair of magnetic members defines the wave transmission path. An inner cylindrical member 21, which is here shown as solid but which may be tubular, is enclosed coaxially disposed within an outer cylindrical member 22. For feeding the input end of the transmission path with signal power, there is provided an input transducer 23 across which is connected the signal source 24 and which comprises several turns of an electrical conductor wound about the inner member 21 of the coaxial pair. Provision is made to have that portion of the signal wave which is launched towards the left initially (in a direction opposite to that desired for transmission) reflected from the left hand end of the path in a manner to combine cumulatively with that portion of the signal wave launched to the right initially. To this end, the left hand end of the coaxial line is shown terminated by a magnetic end plate 25 shunted across the inner and outer members. Alternatively, arrangements can be devised for making this left hand end termination substantially reflectionless, as by the insertion of energy dissipative material to absorb incident wave energy in the manner familiar to workers in the art. Signal energy

can be abstracted at the right hand end of the path by a similar arrangement of an output transducer 26 for supplying a utilization apparatus or load 27. Here too, provision should be made either for making this end of the path substantially reflectionless or for insuring that any such reflections provide energy which adds cumulatively to that being supplied directly to the load.

It should be evident at this point that many of the techniques known to the art applicable to conventional wave guide transmission systems can be utilized here for impressing signal waves from a plurality of sources to a common transmission path, for supplying a plurality of loads with signal energy by way of a common transmission path, and for effecting selectively directive transmission along a transmission path.

It is characteristic of the electromagnetic field patterns in the dielectric propagating medium filling the interspace between the inner and outer members 21 and 22 that, if it be assumed that the members are perfect non-conductors, the electric lines are circular and coaxial with the inner and outer members while the magnetic lines of force extend radially between the inner and outer members as well as having an axial component due to the permeability of the "conductors" not being infinite. As will be evident to a worker in the art, such an electric line pattern is similar to that of a TE_{01} wave in a circular electric wave guide but, unlike such a circular electric wave guide, a coaxial line in accordance with the invention is not inherently high-pass but rather will operate down to as low a frequency as permits good coupling at the terminals. The field configurations in a coaxial line in accordance with the invention are in still further contrast with the case of conventional coaxial transmission lines of electrical conductors in which the field pattern in the propagating medium between the inner and outer members comprises circular magnetic lines and electric lines which are mainly radial but have a small axial component due to the imperfect conductivity of the electrical conductors. There are techniques known in the art for converting to and from an electromagnetic wave having field patterns characterized by radial electric lines and circular magnetic lines from and to, respectively, an electromagnetic wave having field patterns characterized by radial magnetic lines and circular electric lines. The principles applicable, together with typical arrangements, are described on pages 352 through 364 of a book by G. C. Southworth, entitled "Principles and Applications of Waveguide Transmission," published by D. Van Nostrand Company, Inc., New York (1950). Accordingly, it is contemplated that transmission lines in accordance with the principles of the invention can be utilized as elements in conventional forms of wave transmission systems in conjunction with arrangements for conversion of the field patterns of the signal waves.

A characteristic of a coaxial transmission line in accordance with the invention is that when loaded with material of dielectric constant greater than unity its losses (which are primarily magnetic rather than conduction losses) will decrease rather than increase and its impedance, viewed as the ratio of magnetizing force to magnetic flux density will increase. This is in contrast to the conventional coaxial transmission line utilizing conductive members where the introduction of dielectric loading lowers the impedance and increases the conduction losses. Accordingly, the continuing discoveries of dielectric materials of higher and higher dielectric constants will make possible transmission lines in accordance with the invention of lower and lower attenuation and higher and higher impedances, both of which factors are generally desirable. Additionally, by the use of electrical non-conductors as members there is avoided the skin effect characteristic of such conductors, and hence a substantial part of the cross-section of the magnetic elements rather than only a thin skin is useful.

Fig. 3 is a cross section of a coaxial transmission line

30 comprising inner and outer members 31 and 32, respectively, of a material having a high permeability but a low conductivity, such as one of the ferrites, and in which the interspace 33 between the inner and outer member is of a medium having a high dielectric constant and low dielectric losses such as barium titanate or titanium dioxide. This medium may be continuous or comprise spaced septa of material having a high dielectric constant. In Fig. 4, there is shown a short section of a coaxial line 40 in which loading is provided by spaced dielectric septa 41 in the interspace 42 between inner and outer magnetic members 43 and 44, respectively.

There are various ways of loading or controlling the impedance and phase velocity characteristics of a coaxial type embodiment of the invention. In the embodiment 50 shown schematically in Fig. 5, the desired loading is achieved by providing regularly spaced transverse cuts or discontinuities 51 in the longitudinal direction in the outer magnetic member 52 while the inner member 53 is continuous. In the embodiment 60 shown schematically in Fig. 6, the loading is achieved by providing relatively short transverse cuts or discontinuities 61 in the longitudinal direction in the inner member 62 while the outer member 63 is continuous. In each of the last two embodiments, additional loading may be achieved by the insertion in the interspace between the inner and outer members of the coaxial line of a medium or spaced septa of material having a high dielectric constant as discussed above. Additionally, for some applications electrically conducting septa may be substituted.

In order to have the wave energy confined by magnetic admittances rather than electrical admittances, it is desirable that in a coaxial line in accordance with the invention the electrical impedance of the bounding members in the peripheral direction not be low. However, if the coaxial members are of a magnetic material which also has a high dielectric constant, the electrical impedance in the peripheral direction will tend to be low. To achieve a high electrical impedance of the bounding members in the peripheral direction even with material of a high dielectric constant, it is advantageous to laminate the inner and outer members such that they comprise a series of longitudinal strips or segments peripherally disposed. There is shown in Fig. 7 a cross section of coaxial line 70 of this kind in which both the inner and outer magnetic portions 71 and 72 are laminated in the peripheral direction. It is also advantageous in such a line to have the interspace 73 a medium of high dielectric constant. Additionally, either the inner or the outer member may be segmented longitudinally in accordance with the principles illustrated by the lines shown in Figs. 5 and 6.

Each of the various arrangements described above has utilized two distinct boundaries for confining the magnetic field of the transmitted wave. It is feasible instead to enclose the magnetic field of the transmitted wave completely by a single boundary. The hollow cylindrical magnetic wave guide 80 shown in Fig. 8 essentially corresponds to the coaxial line embodiments described above with the elimination of one of the two coaxial members and can be used in an analogous fashion as the wave guiding element in a transmission system. If this wave guide is treated as though the inner magnetic member is omitted, the lines of magnetic force are made to return through the central area 81 without the aid of a high permeability inner member. Conversely, the cylindrical wave guide can be operated to correspond to the inner member of a coaxial pair and the magnetic field can return through outer space. In such a case, the cylindrical wave guide can be simply a wire of electrical non-conducting magnetic material, and the propagating medium of the surrounding space.

An important form in which the principles of the invention may be embodied is a hybrid wave guide in which wave energy of one mode is guided along a trans-

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mission path by the usual techniques for confining the electric field of the wave while at the same time wave energy of different mode is guided along the same path by techniques of the kind set forth above for confining the magnetic field of the wave. In this way, the one hybrid guide may serve as a common transmission path for waves both of a circular electric mode and waves of the more conventional circular magnetic mode.

Fig. 9 illustrates in cross section a coaxial hybrid line 90 of this kind. Inner and outer members 91 and 92 are high-permeability non-conductors and form a coaxial line of the kind described above in connection with Fig. 2, suitable for propagating waves in which the electric lines in the interspace 93 are circular. Additionally, the outer surface of the inner magnetic member 91 and the inner surface of the outer magnetic member 92 are lined with spaced thin longitudinal strips 93 of an electrical conductor, such as copper, to provide continuous electrical conductivity in the longitudinal direction, although not in the circumferential direction. As a result of this latter consideration, these conductive strips have little effect on a circular electric wave. The strips, however, serve to form inner and outer conductive members of a conventional form of coaxial line since the dominant mode of a conventional coaxial line requires only longitudinal conductivity. For good transmission of the conventional mode it is advantageous that the spacing between adjacent strips be small relative to the width of the strips. A hybrid coaxial line of this kind can be utilized to transmit efficiently and independently circular electric and circular magnetic waves.

Fig. 10 illustrates a possible modification of the coaxial line shown in Fig. 9. A plurality of spaced cylindrical layers 94 of a material of high dielectrical constant but low dielectric loss is disposed in the interspace between inner and outer magnetic members 91 and 92 to achieve the desired loading discussed above for transmission in the circular electric mode. To minimize the undesirable effect on the transmission of the conventional circular magnetic mode, it is preferable to interpose layers 95 of low dielectric constant intermediate the layers 94 of high dielectric constant.

Fig. 11 shows a modified version 100 of the hybrid coaxial line 90 shown in Fig. 9. In coaxial line 100, inner and outer electrically conductive members 102 and 101, respectively, make up a conventional form of coaxial line for the propagation of circular magnetic waves. The outer surface of inner member 101 and the inner surface of outer member 102 are lined with spaced longitudinal strips 103 for forming inner and outer magnetic members of a coaxial line of the kind described above with reference to Fig. 7 for the propagation of a circular electric wave.

Fig. 12 shows a modification of the arrangement of Fig. 9 in which both the magnetic conductors and electric conductors are laminated in the peripheral direction to provide a series of longitudinal strips, each having a layer 111 of material of high permeability and low conductivity and a layer 112 of material of high conductivity. Additionally, it is possible to transpose the layers in the manner suggested by a comparison of the lines shown in Figs. 9 and 11.

It can be seen that these principles for permitting simultaneous transmission of independent circular electric and circular magnetic modes can be applied to the various embodiments illustrated in Figs. 1, 5, 6, 7 and 8.

It is also to be understood that the various embodiments described are illustrative of the general principles of the invention. Various other arrangements may be devised by a worker skilled in the art without departing from the spirit and scope of the invention. For example, the principles have been set forth with special reference to application to transmission lines whereas these principles can similarly be applied to the construc-

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tion of other forms of transmission elements, such as delay lines, resonators, and impedance matching apparatus.

What is claimed is:

1. In combination a wave guide comprising inner and outer coaxial elements each of ferromagnetic material of high resistivity compared to metals, a wave-sustaining dielectric medium between said elements for transmission of electromagnetic waves, means at one point of said line for launching in said medium transverse electric electromagnetic waves having a field pattern of circular lines of electric force and radial lines of magnetic force and of frequency at which the permeability of said ferromagnetic material is high, and means at another point of said line for abstracting wave energy from the field for utilization.

2. In combination a wave guide comprising inner and outer coaxial elements each of ferromagnetic material of high resistivity compared to metals and a wave-sustaining medium for transmission of electromagnetic waves located between said elements and comprising material of dielectric constant substantially greater than unity, means at one point of said line for launching in said medium transverse electric electromagnetic waves having a field pattern of circular lines of electric force and radial lines of magnetic force and of frequency at which the permeability of said ferromagnetic material is high, and means at the opposite end of said line for abstracting the wave energy therefrom for utilization.

3. In a wave transmission system, a wave guide comprising an inner member including an elongated core of ferromagnetic material of high resistivity compared to metals and a plurality of strips of metallic conductor arranged longitudinally and cylindrically to partially surround said core, a coaxial outer hollow cylindrical element of ferromagnetic material of high resistivity compared to metals, and a plurality of strips of metallic conductor arranged longitudinally on the inner surface of said hollow cylindrical element to partially cover said surface, means at one point of said line for applying for propagation along said medium transverse electric electromagnetic waves of frequency at which the permeability of said ferromagnetic material is high, and separate transverse magnetic electromagnetic waves, and means at another point of said line for abstracting both said waves for utilization.

4. A wave transmission system according to claim 3 in which the space between said coaxial members includes concentric cylinders of material having a dielectric constant substantially greater than unity extending the length of said members.

5. A combination according to claim 1 including a plurality of septa of material having a high dielectric constant spaced apart from one another and extending between said inner and outer coaxial elements.

6. The combination according to claim 1 in which said inner coaxial element is continuous and said outer coaxial element comprises a series of cylindrical members spaced apart from one another in axial alignment.

7. The combination according to claim 6 in which said wave-sustaining dielectric medium comprises material of dielectric constant substantially greater than unity.

8. The combination in accordance with claim 1 in which said inner coaxial element comprises a succession of members spaced apart from one another.

9. The combination according to claim 8 in which said wave-sustaining dielectric medium comprises material of dielectric constant substantially greater than unity.

10. The combination according to claim 1 in which at least one of said coaxial elements is laminated for forming a series of longitudinal segments peripherally disposed.

11. The combination according to claim 10 in which said wave-sustaining dielectric medium comprises ma-

material of dielectric constant substantially greater than unity.

References Cited in the file of this patent

UNITED STATES PATENTS

2,129,711	Southworth	Sept. 13, 1938
2,231,602	Southworth	Feb. 11, 1941
2,452,529	Snoek	Oct. 26, 1948
2,511,610	Wheeler	June 13, 1950
2,611,094	Rex	Sept. 16, 1952
2,644,930	Luhrs	July 7, 1953
2,645,758	Van De Lindt	July 14, 1953
2,650,350	Heath	Aug. 25, 1953

2,694,796
2,745,069
2,777,896
2,779,923
2,779,925
2,784,378
2,799,006
2,825,759
2,825,761
2,832,938

5

10

603,119

Rowland	Nov. 16, 1954
Hewitt	May 8, 1956
Black	Jan. 15, 1957
Purcell	Jan. 29, 1957
Black	Jan. 29, 1957
Yager	Mar. 5, 1957
Edson	July 9, 1957
Clogston	Mar. 4, 1958
Kreer	Mar. 4, 1958
Rado	Apr. 29, 1958

FOREIGN PATENTS

Great Britain	June 9, 1948
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