United States Patent

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[73] Assignee **General Electric Company**

[54] **DIRECTIONAL COUPLER FOR OVERSIZE CIRCULAR WAVEGUIDES**
18 Claims, 4 Drawing Figs.

[52] **U.S. Cl.** **333/10,** 333/98
[51] **Int. Cl.** **H01p 5/14,** H01p 1/00
[50] **Field of Search** 333/10, 98

[56] **References Cited**
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ABSTRACT: A directional coupler, for use in the propagation of microwave frequency electromagnetic energy, comprises a septum connected diagonally across a right angle junction of two circular waveguides. The septum is a metallic grid comprised of a plurality of substantially parallel electrical conductor of diameter much smaller than the wavelength of the propagated frequency, and the spacing between adjacent parallel conductors is also smaller than the propagation wavelength. The plurality of conductors may form a grid of equal size squares or a series of nested ellipses, and provide uniform complex reflection and transmission coefficients over the entire septum.

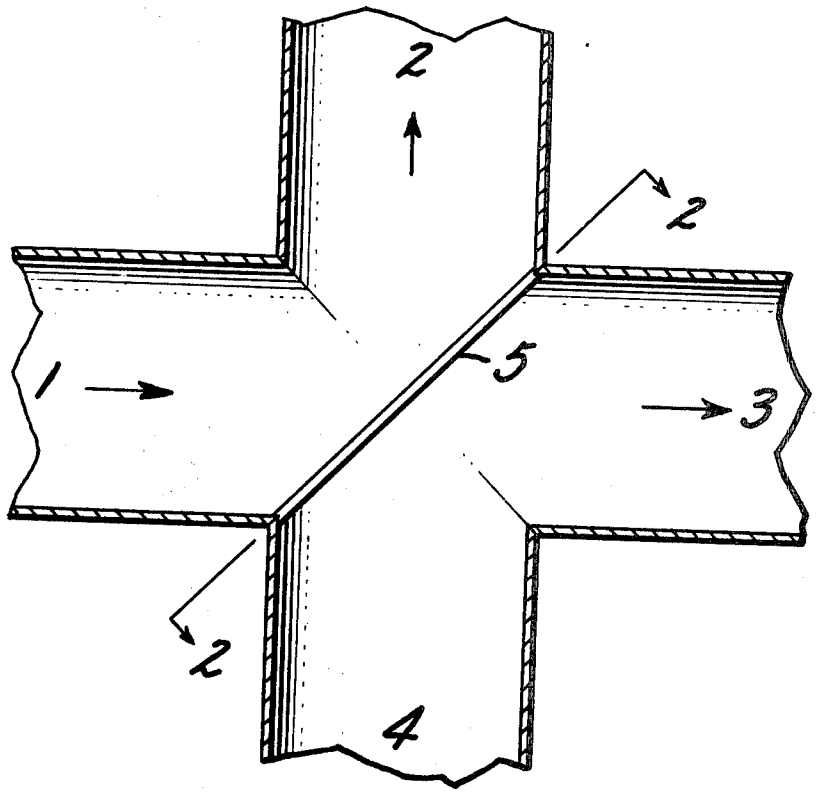


Fig. 1.

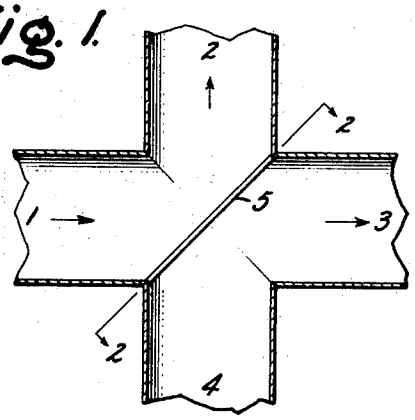


Fig. 2.

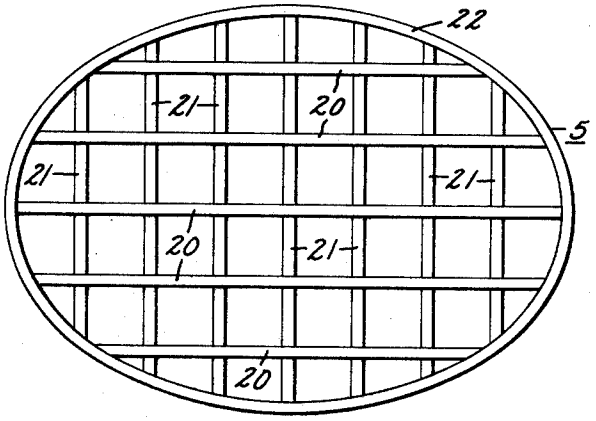
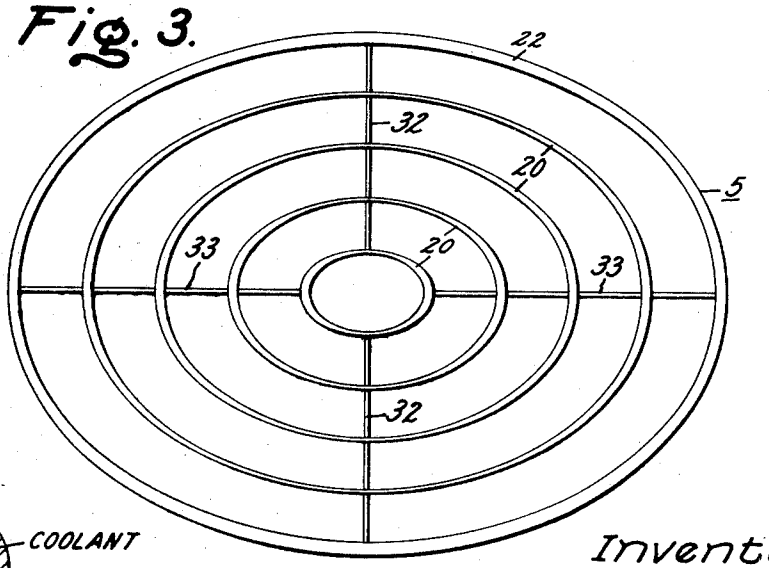


Fig. 3.



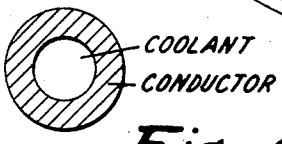


Fig. 4.

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DIRECTIONAL COUPLER FOR OVERSIZE CIRCULAR WAVEGUIDES

My invention relates to a waveguide component for controlling the reflected and transmitted portions of a desired mode of microwave frequency electromagnetic energy propagation at a right angle junction of two oversize circular waveguides, and in particular to a directional coupler providing substantially uniform complex reflection and transmission coefficients over an entire septum comprising the coupler. The invention herein described was made in the course of or under a contract AF30(602)3810 with the Department of the Air Force.

Waveguides are conventionally employed for the propagation of low and medium power level signals in the microwave frequency band. Recently, it has been suggested that waveguides may also be utilized as low loss, high efficiency transmission devices for transmission of bulk electric power. The use of waveguides for the transmission and control of very high average power at CW microwave frequency requires the use of oversize waveguides to obtain a low loss transmission line. As a typical example, the transmission of bulk power in the order of 10^7 watts of power in the $TE_{01}°$ mode at x-band frequency through a waveguide is obtained without excessive heating thereof by employing an oversize circular aluminum waveguide having an inner diameter of approximately 30 inches. Such oversize dimension reduces the waveguide attenuation by approximately four orders of magnitude as compared to the attenuation characteristics of conventional size waveguides, thereby producing the required low loss transmission line. The $TE_{01}°$ mode may obviously also be used in lower power applications for long distance transmission where the low attenuation characteristics of oversize circular waveguides is desirable.

Although the use of oversize waveguides is feasible for the transmission of bulk (and low) power at CW microwave frequencies, the application may be limited by other waveguide components in the microwave system. A waveguide device, commonly described as a directional coupler, and in particular a cross-guide coupler connected diagonally across a right angle junction of two waveguides, interconnects such waveguides and controls the electromagnetic energy propagation in the other arms of the waveguides due to an incident power in an input arm thereof. Thus, in order to have bulk power transmission at microwave frequency economically feasible, it is necessary to provide a directional coupler for interconnecting two oversize circular waveguides at a right angle junction, and having desired reflection and transmission characteristics, and capable of fabrication economically.

Therefore, one of the principal objects of my invention is to provide a directional coupler for interconnecting two oversize circular waveguides at a right angle junction.

Another object of my invention is to provide the coupler with characteristics of substantially uniform complex reflection and transmission coefficients over the entire surface of the coupler.

Another object of my invention is to economically fabricate the coupler from a plurality of substantially parallel electrical conductors to form a grid of equal size squares or nested ellipses.

Briefly summarized, my invention is a directional coupler in the form of a metallic grid septum connected diagonally across a right angle junction of two oversize circular waveguides and providing uniform complex reflection and transmission coefficients over the entire septum. The grid may be in the form of two pluralities of equally spaced electrical conductors, the two pluralities being perpendicular to each other to form a grid of equal size squares. In a second embodiment, the electrical conductors are disposed in a series of nested ellipses and the conductors are of larger predetermined diameter along the major axes of the ellipses than along the minor axes. The spacing between adjacent conductors is a predetermined dimension along the major axes which is greater than the spacing along the minor axes.

The features of my invention which I desire to protect herein are pointed out with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing, wherein like parts of each of the several figures are identified by the same reference character and wherein:

FIG. **1** is a top view, partly in section, illustrating my directional coupler connected diagonally across a right angle junction of two circular waveguides;

FIG. **2** is a view along line **2–2** in FIG. **1** illustrating the equal square grid embodiment of my invention;

FIG. **3** is a view along line **2–2** in FIG. **1** illustrating the confocal ellipse grid embodiment of my invention; and

FIG. **4** is a cross-sectional view of one of the conductors in the FIGS. **2** or **3** embodiments for very high power applications of the directional coupler.

There are many types of directional couplers for use with normal size waveguides, however, for use with high power, oversize circular waveguides, a directional coupler comprising a planar metallic septum connected across a right angle junction of two oversize circular waveguides as illustrated in FIG. **1** appears to be the only feasible-type. Thus, septum **5** is connected diagonally across the junction of a first oversize circular waveguide comprising arms **1**, **3** and a second oversize circular waveguide comprising arms **2**, **4**, the longitudinal axes of adjacent arms intersecting at a right angle. It is assumed that a plane wave of incident microwave electromagnetic energy in a desired mode is propagating toward the septum through circular waveguide **1** as indicated by the arrow. The planar septum must have suitable reflection and transmission coefficients for the plane wave incident at an angle of 45° to the septum normal to provide a desired reflection of the incident electromagnetic energy into circular waveguide arm **2** and a desired transmission into arm **3**, no coupling theoretically occurring in arm **4**.

Two problems are immediately apparent with the septum approach for utilization with circular waveguides. In the case of a rectangular waveguide and a $TE_{10}^{\square}$ mode incident on a 45° septum, the angle between the plane of incidence and the incident wave polarization is the same over the entire septum. However, in the case of the $TE_{0n}°$ modes the angle varies, and the septum must be designed to compensate for this variation or else undesired reflections and transmissions occur in waveguide arms **2** and **3**, respectively, over particular portions of the septum. Thus, the reflection and transmission coefficients to a plane wave incident at 45° to the septum normal must be constant in magnitude and phase (i.e. uniform complex reflection and transmission coefficients) over the entire septum in a directional coupler adapted for circular waveguides. The second problem is the requirement for cooling of the septum at the high power levels for which the oversize waveguides are obviously intended. As previously stated, the $TE_{0n}°$ modes can also be used in low power applications where the low attenuation characteristic of oversize circular waveguides is desirable in which case the septum presents no cooling problem.

A first embodiment of a metallic septum which is adapted to function as a directional coupler in oversize circular waveguides in accordance with my invention is illustrated in FIG. **2**. The directional coupler or septum comprises a grid of metallic cylindrical, electrical conductors (i.e. wires), the septum being elliptical in outline to conform to the outline of the plane disposed diagonally across the right angle junction of the two circular waveguides. Two sets of the conductors are provided, one set **20** being perpendicular to the other set **21**, the conductors in each set being parallel to each other, and adjacent conductors in each set being equally spaced to form a grid of equal size squares. The conductors **20** are parallel to the plane including the longitudinal axes of the two intersecting circular waveguides. The spacing between adjacent conductors is smaller than a wavelength of the particular frequen-

cy of electromagnetic energy being propagated through the waveguide, and the diameter of each conductor is much smaller than such wavelength. For both the FIGS. 2 and 3 embodiments, the conductor spacing and diameter are preferably as large as possible, consistent with the spacing versus diameter relationship to be hereinafter described, the dimensions being limited by the heat removal problem of small diameter conductors and the structural rigidity problem of a septum constructed therefrom. The reflection coefficient R may be determined from the following known relationship for a grid of only one set of parallel conductors.

$$R=\left[\frac{E_z^s}{E_z^p}\right]_{x=0}=\frac{-1}{1+i\frac{d}{2\lambda}\cos\theta\cos\phi_0\ln\left(\frac{d}{2\pi a}\right)}$$

This equation is applicable for both parallel and perpendicular polarizations of the incident wave at arbitrary angles of incidence at the septum. The transmission coefficient

$$|T|=\sqrt{1-|R|^2}$$

for an assumed lossless septum. E_z^s and E_z^p are the z components of the scattered and incident fields, respectively. The conductors of the septum are in the yz plane and parallel to the z axis. d is the center-to-center spacing of adjacent conductors and a is the conductor radius. Θ is the angle between the incidence direction and the xy plane and Φ_0 is the angle between the x axis and the projection of the incidence direction on the xy plane. It can be seen that for parallel polarization of the wave front, $\Theta=45°$ and $\Phi_0=0$ whereas for perpendicular polarization, $\Theta=0°$ and $\Phi_0=45°$. Thus, the reflection coefficient R (and transmission coefficient) is the same (i.e. uniform) in magnitude and phase over the entire septum for a given d, λ, and a, for both parallel and perpendicular polarization, which is the desired characteristic.

In the case of perpendicular polarization of the incident wave front, the x and y components of electric fields E^s and E^p are zero whereas for parallel polarization, the y components are zero and the x components are equal in magnitude of the z components for both E^s and E^p. Thus, it is evident that the total reflected wave for one polarization is the same in magnitude and phase as for the other polarization. A septum constructed of horizontal and vertical conductors (as indicated in FIG. 2) with the same spacing in both directions thus provides the same reflection in magnitude and phase over the entire septum for very thin conductors of very high conductivity, and the reflection is the same where the polarization is either parallel or perpendicular. At the points along the septum where the polarizations is neither parallel nor perpendicular, the polarization vector can be separated into parallel and perpendicular components, each of which are reflected in the manner indicated above.

The two sets of cylindrical electrical conductors forming a grid of equal size squares are illustrated in FIG. 2 as equally spaced, parallel horizontal conductors **20** and vertical conductor **21**. A means for retaining the ends of the conductors in fixed relationship, maintaining the septum in a planar orientation, and providing structural rigidity to the septum is obtained by an elliptically shaped frame member **22** to which the conductor ends are suitably connected. The frame member-septum is then connected across the diagonal juncture of the circular waveguides as indicated in FIG. **1**. If a $TE_{0n}°$ mode is used, frame member **22** may be fabricated of virtually any material since the electric field in the region of the waveguide surface is zero. The electrical conductors **20** and **21** are each of equal diameter, fabricated of a material such as copper or steel, and possibly silver coated for increased conductivity. The conductors **20**, **21** at the corners of the squares forming the grid may be in electrical contact (i.e. effectively being coplanar) or, such overlapping conductors may be electrically insulated from each other (i.e. forming two separated parallel planes), the effect of the electrical contact or isolation on the complex reflection and transmission coefficients being relatively unimportant. In the case of the corners being in electrical contact, the overlapping conductors may be mechanically connected at such corners, or each horizontal (or vertical) conductor may be divided into segments of length equal to one side of the square, and the septum fabricated into a truly coplanar device.

A specific example of the FIG. 2 embodiment of my invention is the 3 db. coupler wherein 50 percent of the incident power is reflected into waveguide arm **2** and 50 percent is transmitted into arm **3**. From the above formula, and other practical considerations, the spacing d between adjacent parallel conductors should be a maximum of approximately 0.50λ, and the conductor radius being 0.02λ when $d=0.50\lambda$. Spacing d of somewhat less than 0.585λ is necessary to prevent the formation of higher order modes.

The application of my FIG. 2 septum as a 20 db. coupler (1 percent of incident power reflected and 99 percent transmitted) is not possible without spacings considerably greater than one wavelength. However, the 20 db. coupler can be designed for reflecting 99 percent of the incident power and transmitting 1 percent by utilizing a conductor spacing of $d=0.50\lambda$ and a conductor radius $a=0.071\lambda$.

Since the conductors are thinner for the 3 db. coupler, it performs better electrically than the 20 db. coupler, however, the problem of heat removal is obviously greater. The maximum electrical current developed in the waveguide is in the order of the peak incident electric field. For high power transmission in the order of 10^7 watts, the peak electric field is approximately 2×10^5 volts/meter and thus the peak current is approximately 20 amperes. The resistance of a copper or aluminum conductor with the radius of 0.02λ and length of one meter at a frequency of 9GHz. is approximately 4 ohms and thus the heat loss in the conductor is in the order of 1 kilowatt. Since a radius of 0.02λ at a frequency of 9GHz. is equivalent to a diameter of approximately 0.06 inch, the 1 kilowatt heat dissipation requires an external cooling means such as the use of circulating water through a hollow interior of the conductors as illustrated in the cross section view of one of the conductors in FIG. **4**. Water at a pressure of somewhat less than 100 p.s.i. flowing through the hollow conductors having an inner diameter of 0.050 inch produces a sufficiently fast flow to limit the maximum water temperature rise to approximately 10° F. The spacing of 0.50λ between adjacent parallel conductors is approximately 0.75 inch at the frequency of 9GHz. For some applications, the grid of equal size squares having dimensions of the order described hereinabove may require an additional structural support in order to maintain the grid in a reasonably flat position. My FIG. 2 embodiment directional coupler is adapted for use with propagation of the $TE_{01}°$, $TE_{02}°$—$_{0n}°$ modes, as well as the $TE_{11}°$ mode.

FIG. 3 illustrates a second embodiment of my directional coupler wherein a septum comprising a plurality of electrical conductors **20** is again formed in a planar array having an elliptical outline as in the case of the FIG. 2 embodiment, and is adapted to be connected diagonally across the right angle junction of two oversize circular waveguides by means of frame member **22**. In the FIG. 3 embodiment, however, the grid of conductors are disposed in a series of nested ellipses and the conductors are therefore merely substantially parallel, rather than exactly parallel as in the case of the FIG. 2 embodiment. The coincident major axes of the ellipses are in the plane including the intersecting longitudinal axes of the two oversize circular waveguides. Conductors **20** are circular in cross section as in the case of the FIG. 2 embodiment.

The FIG. 3 embodiment has the advantage of eliminating the conductors which are perpendicular to the polarization of the incident wave as in the case of FIG. 2, however, the curvature of the conductors and the unequal spacing between conductors of adjacent nested ellipses tends to introduce errors which must be compensated for by varying the diameters of the conductors in order to preserve substantially uniform complex reflection and transmission coefficients over the en-

tire septum. Support members **32** and **33** in the form of perpendicularly disposed tubular or solid members fabricated of an electrically conductive or electrically insulated material are employed to retain the conductors **20** in nested elliptical relationship (i.e. equal spacing along the major and minor axes of the concentric ellipses) and provide structural rigidity to the septum. The two support members **32** are located along the minor axes of the nested ellipses formed by conductors **20** and support members **33** are located along the major axes and are suitably connected to the overlapping conductors **20** thereat. The outer ends of support members **32** and **33** are suitably connected to frame member **22**. Support members **32, 33** also cause slight perturbations over the septum.

The adjacent conductors **20** in the nested elliptical grid are each equally spaced along the major axes and are equally spaced at a smaller distance along the minor axes of the ellipses. This requirement is deduced from the above equation wherein the factor $d/\lambda \ln(d/2\pi a)$ must be constant in order to preserve the uniform complex reflection and transmission coefficients. Thus, in an elliptical grid, the conductors become of greater diameter ($2a$) as the spacing d between adjacent conductors becomes smaller. As an example, in the case of a 3 db. coupler,

$$2\frac{d}{\lambda}\cos\theta\cos\phi_0 \ln\left(\frac{d}{2\pi a}\right)=1.0$$

whereby

$$\frac{d}{\lambda}\ln\left(\frac{d}{2\pi a}\right)=\frac{1}{2\cos\theta\cos\phi_0}=0.707$$

Thus, for a 3 db. directional coupler comprising a grid of electrical conductors disposed in nested elliptical relationship, a typical spacing d between adjacent conductors and conductor radius a is 0.5λ and 0.02λ, respectively, along the major axis, and 0.3535λ and 0.00767λ, respectively, along the minor axis. The nested elliptical grid coupler is adapted for use with propagation of the $TE_{01}°$, $TE_{02}°$—$TE_{0n}°$ modes.

From the foregoing description, it can be appreciated that may invention makes available a new directional coupler for circular waveguides which is especially adapted for very high power applications, although it is also useful in low power applications where the low attenuation characteristics of oversize circular waveguides is desirable. The coupler comprises a grid of substantially parallel electrical conductors which in a first embodiment include two pluralities forming equally size squares, and in a second embodiment form nested ellipses. The conductors in the equal square grid are of equal diameter but in the case of the nested elliptical grid the diameter of the conductors varies in an inverse manner with the spacing between adjacent conductors. The particular spacing between adjacent conductors and conductor diameter in accordance with my invention preserves uniform complex reflection and transmission coefficients over the entire septum of the coupler to thereby provide desired reflection and transmission into the circular waveguide arms connected to the directional coupler. The relatively simple structure of my couplers is capable of economical fabrication.

Having described two particular embodiment of my directional coupler, the intended scope of my invention is defined by the following claims.

I claim:

1. A directional coupler for circular waveguides comprising a grid of substantially parallel conductors including:

a first plurality of parallel cylindrical electrical conductors,

a second plurality of parallel cylindrical electrical conductors, the second plurality disposed perpendicular to and substantially coplanar with the first plurality,

each conductor of predetermined diameter much smaller than one wavelength λ of the frequency of the electromagnetic energy being propagated through the waveguides, the spacing between adjacent parallel conductors being predetermined and smaller than one wavelength to provide substantially uniform complex reflection and transmission coefficients over the entire grid, said grid having an elliptical outline for connection diagonally across a right angle junction of two circular waveguides, and

means for retaining the conductors in spaced apart relationship, said means adapted for connecting said grid diagonally across the right angle junction of two circular waveguides.

2. A directional coupler for circular waveguides comprising a grid of substantially parallel conductors including:

a plurality of electrical conductors disposed in a planar grid of nested ellipses,

each conductor of predetermined diameter much smaller than one wavelength λ of the frequency of the electromagnetic energy being propagated through the waveguides, the spacing between adjacent parallel conductors being predetermined and smaller than one wavelength to provide substantially uniform complex reflection and transmission coefficients over the entire grid, said grid having an elliptical outline for connection diagonally across a right angle junction of two circular waveguides, and

means for retaining the conductors in spaced apart relationship, said means adapted for connecting said grid diagonally across the right angle junction of two circular waveguides.

3. The directional coupler set forth in claim **1** wherein each conductor is of equal diameter, and adjacent conductors in each plurality of conductors is equally spaced to form a substantially planar grid of equal size squares.

4. The directional coupler set forth in claim **2** wherein adjacent conductors are equally spaced along the major axes of the nested ellipses.

5. The directional coupler set forth in claim **2** wherein each conductor is of variable diameter, each conductor being of a first equal diameter along the major axes of the ellipses and of a second smaller equal diameter along the minor axes.

6. The directional coupler set forth in claim **3** wherein the conductors are in overlapping relationship and in electrical contact at the corners of the squares in the grid of conductors.

7. The directional coupler set forth in claim **3** wherein the conductors are in overlapping relationship and electrically insulated at the corners of the squares in the grid of conductors.

8. The directional coupler set forth in claim **3** wherein the spacing between adjacent parallel conductors is a maximum of approximately 0.50λ wherein λ is the wavelength of the particular frequency of electromagnetic energy being propagated through the circular waveguides, and the conductor radius is approximately 0.02λ for a 3 db. directional coupler.

9. The directional coupler set forth in claim **4** wherein:

adjacent conductors are equally spaced along the minor axes of the nested ellipses.

10. The directional coupler set forth in claim **9** wherein:

the spacing between adjacent conductors along the major axes is greater than the spacing along the minor axes,

11. The 3 db. directional coupler set forth in claim **8** and further comprising:

means for cooling the conductors to thereby permit high power propagation through the circular waveguides, the waveguides being oversize to obtain a low attenuation characteristics.

12. A directional coupler for high power, oversize circular waveguides in which high power electromagnetic energy at x-band frequency is propagated comprising:

an elliptically shaped septum connected diagonally across two oversize circular waveguides intersecting at right angles, said septum comprising:

a planar grid comprising at least one plurality of substantially parallel, electrical conductors of predetermined diameter much smaller than one wavelength λ of a particular x-band frequency of the electromagnetic energy being propagated through the waveguides, a predetermined spacing between adjacent parallel conductors being smaller than one wavelength of the propagated x-

band frequency to provide substantially uniform complex reflection and transmission coefficients over the entire septum and thereby obtain desired reflection and transmission in the waveguide arms controlled by the directional coupler.

13. The directional coupler set forth in claim 12 wherein said at least one plurality of conductors comprises:

a first plurality of parallel conductors which are parallel to the plane including the intersecting longitudinal axes of the two oversize circular waveguides, and

a second plurality of parallel conductors which are perpendicular to the first plurality,

said directional coupler adapted for waveguide propagation of the $TE_{01}°$, $TE_{02}°$—$TE_{0n}°$ modes and the $TE_{11}°$ mode for which the uniform complex reflection and transmission coefficients are preserved.

14. The directional coupler set forth in claim 12 wherein said at least one plurality of conductors comprises:

one plurality of substantially parallel conductors forming a like plurality of nested ellipses, the coincident major axes of the ellipses, being in the plane including the intersecting longitudinal axes of the two oversize circular waveguides,

said directional coupler adapted for waveguide propagation of the $TE_{01}°$, $TE_{02}°$—$TE_{0n}°$ modes for which the uniform complex reflection and transmission coefficients are preserved.

15. The directional coupler set forth in claim 13 wherein:

each conductor being of equal diameter of radius approximately equal to 0.02λ for a 3 db. coupler,

adjacent conductors in each plurality of conductors being equally spaced a maximum of approximately 0.50λ for a 3 db. coupler to form a grid of equal size squares.

16. The directional coupler set forth in claim 14 wherein:

adjacent conductors are equally spaced along the major axes of the nested ellipses.

17. The directional coupler set forth in claim 16 wherein:

adjacent conductors are equally spaced along the minor axes of the nested ellipses.

18. The directional coupler set forth in claim 17 and further comprising:

means for supporting said plurality of conductors and for retaining adjacent conductors equally spaced along the major and minor axes of the nested ellipses.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,579,148 Dated May 18, 1971

Inventor(s) Alan E. Blume

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In Column 4, line 28, change "peak incident electric field" to - peak incident electric field 10^4 -

In Column 5, line 39, change "may invention" to - my invention -

In Column 7, line 21, cancel the comma after "ellipses"

Signed and sealed this 18th day of January 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Acting Commissioner of Patents