FIG. 5

FIG. 6
This invention relates to directional couplers and more particularly to an interdigitated quadrature strip line coupler. A directional quadrature coupler is a four port microwave junction with properties such that a wave incident in port one couples power into ports two and three, but not into port four. Similarly, power incident in port four couples into ports two and three but not into port one. Thus, ports one and four are uncoupled. A wave incident in port two or three couples power into ports one and four only, thus ports two and three are also uncoupled. If three of the four ports are terminated in matched loads, the fourth port appears terminated in a matched load, and an incident wave in this port will not be reflected.

In one application, directional couplers are used to divide the power between two amplifiers to reduce the terminal voltage standing wave ratio (VSWR) and increase circuit design flexibility. Ideally, a coupler should be lossless with exactly 3-dB power division across the band. Heretofore, a low loss, low VSWR 3-dB strip line coupler has been difficult to achieve due to line spacing and fabrication tolerances. Both the branch line coupler and the non-interdigitated edge-coupled coupler are among those which are difficult to fabricate due to the tolerance requirements. Further, branch line couplers are not capable of simultaneously meeting the VSWR and bandwidth objectives of most coupling requirements within a reasonable number of sections. The tandem coupler also has severe limitations and, in addition, is rather large dimensionally. In addition, both these configurations have a narrow bandwidth and require a much larger substrate than single-sectioned coupled line couplers.

Tight coupling in directional couplers for microwave integrated circuits has also been achieved by means of broadside coupling and re-entrant sections. Both these configurations, however, require multilayer circuitry, which is very difficult to build on ceramic, and virtually impossible in the case of monolithic integrated circuits.

An object of the present invention is to provide a low loss quadrature coupler. Another object of this invention is to provide a wide bandwidth quadrature coupler. Still another object of this invention is to provide a quadrature coupler having reasonable fabrication tolerances. Further, object of this invention is to provide a quadrature coupler having interdigitated strip line sections.

In accordance with the present invention, several strip line sections are formed on a substrate in an interdigitated pattern. Alternate line sections are tied together by jumper wires bonded thereto. The effective length of each line section is on the order of a quarter wavelength at the bandwidth center frequency. The design of the input ports is symmetrical with the interdigitated line sections, thus improving the coupling characteristics.
and tolerances. The coupler of FIG. 3 includes two outer sections 52 and 54 forming a region of loose coupling each one quarter wavelength long. Typically, the two outer sections 52 and 54 have 17.2-db coupling, which can be realized with edge coupled lines 8 mils wide spaced 16 mils apart on a 20 mil ceramic substrate. If the two outer sections have a 17.2-db coupling, then a center section 56 requires 1.76 db coupling to produce an overall 3-db coupler. The tight coupled center section 56 is again one quarter wavelength long. As illustrated, the section 56 has two spaced lines for edge coupling. The width and spacing of such lines is difficult to calculate and almost impossible to build. In an attempt to use couplers of the type illustrated in FIG. 3, broadband coupling has been considered for the section 56. However, severe problems are encountered in trying to keep the lines overlapped for the complete quarter wavelength, and depositing the very thin ceramic for the line spacing.

With an interdigitated coupler of the type illustrated in FIG. 4, the overall area of the coupler can be reduced to one third that illustrated in FIG. 3, and fabrication procedures are simplified considerably. Referring again to FIG. 4, that a first line section 58 terminates at a port 60 (port one) and a second line section 62 terminates at a port 64 (port three). Ports one and three are thus similar and symmetrical. A third line section 66 terminates at one end at a port 68 (port two) and at the other end at port 70 (port four). Ports 68 and 70 are also formed integral with line sections 72 and 74, respectively, which are half as long as the section 66. Thus, the ports 68 and 70 are symmetrical, and the entire coupler is symmetrical. Symmetry in a coupler of the type illustrated improves the coupling efficiency by lowering losses.

Line sections 58, 62, 66, 72, and 74 form an interdigitated pattern. Alternate line sections are interconnected by crossover wires. Thus, section 58 is connected to section 62 by means of a group of three crossover wires 76 at port 60 and a group of three crossover wires 78 at port 64. Line section 66 connects to the line section 72 by a group of three crossover wires 80 and to the line section 74 by means of a group of three crossover wires 82. Multiple bonding wires for the crossovers are more easily implemented than single crossover wires and reduce the parasitic inductance associated with the bonding wires.

One model of the coupler shown in FIG. 4 was fabricated on 42-um thick substrate of alumina (Al₂O₃) with a ground plane covering one surface. The unglazed alumina was placed in a vacuum chamber and a thin gold film deposited on the other plane of the ground plane. Using photomasking and etch techniques, a first mask was formed over the thin gold film to outline the strip line section. The unwanted film was then removed by etching and a second mask formed on the substrate defining a strip line section and the port areas. Gold was then plated over the exposed gold film areas through the second mask to a desired thickness. In one laboratory model of an interdigitated coupler, the strip line sections are 4.5 mils wide and spaced 3 mils apart. It should be understood that the interdigitated coupler of the present invention is applicable to circuits with two ground planes with either one or two layers of dielectric.

Referring to FIG. 5, there is shown a plot of transmission magnitude in db versus frequency in ghz, for the model described above. For an input coupled to port one, power was transmitted to port three with an attenuation of about 3-db as shown by the curve 86. With the same input connected to port one, power was transmitted to port two with an attenuation of about 3.5-db, as indicated by curve 88. Both these curves are for a frequency range of from 2 ghz to 4 ghz. Between port one and port four, very little power was transmitted as indicated by the curve 90 which is approximately 30 db down. It should be noted that the curves of FIG. 5 are not intended to indicate the peak performance of the coupler of FIG. 4. These curves were plotted from data taken from laboratory experiments.

Referring to Table 1, there is shown the complete response of an interdigitated 3-db coupler of the present invention between 2.0 ghz and 4.0 ghz. In addition to listing the data from which the curves of FIG. 5 were plotted, Table 1 also lists insertion loss and output imbalance. Again, this data is not intended to imply peak performance, but rather represents data obtained from laboratory experiments.

<table>
<thead>
<tr>
<th>Frequency (ghz)</th>
<th>Direct output</th>
<th>Coupled Output</th>
<th>Directivity</th>
<th>Insertion loss</th>
<th>Output Imbalance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>2.9</td>
<td>4.0</td>
<td>SL 6</td>
<td>32</td>
<td>1.40</td>
</tr>
<tr>
<td>2.5</td>
<td>3.0</td>
<td>4.5</td>
<td>20.0</td>
<td>28</td>
<td>0.97</td>
</tr>
<tr>
<td>2.8</td>
<td>3.4</td>
<td>4.0</td>
<td>20.8</td>
<td>27</td>
<td>0.81</td>
</tr>
<tr>
<td>3.2</td>
<td>3.7</td>
<td>4.2</td>
<td>31.4</td>
<td>24</td>
<td>0.58</td>
</tr>
<tr>
<td>3.5</td>
<td>3.8</td>
<td>4.2</td>
<td>31.5</td>
<td>25</td>
<td>0.68</td>
</tr>
<tr>
<td>4.0</td>
<td>3.9</td>
<td>4.5</td>
<td>31.1</td>
<td>15</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Referring to FIG. 6, there is shown another embodiment of an interdigitated coupler in accordance with the present invention. Strip lines 92 and 94 are formed integral with port 96 (port three). These strip lines are connected to port 98 (port two) by means of a crossover wire 100 bonded to the strip lines and the port. A strip line 102 is formed integral with the port 104 (port four) and port 106 (port one). The port 104 is also formed integral with a strip line 108 interdigitated with the strip lines 92 and 94 and connected to the port 106 by means of a crossover wire 110. The strip lines 92, 94, 102, and 108 are a quarter wavelength long at the bandwidth center frequency.

A 3-db interdigitated quadrature coupler in the pattern of FIG. 6 was fabricated on a 40 mil thick substrate of alumina. The design consists of four interdigitated strip lines, each 4.5 mils wide, spaced 3.0 mils apart. Tests run on a model show that losses were less than 0.25 db in the frequency range from 2 ghz to 4 ghz. Isolation 40 db at 2 ghz falling smoothly to 21.5 db at 4 ghz.

In addition to being used as the input and output coupler for an amplifier, the coupler of the present invention may also be used in impedance bridges for microwave measurements and power monitoring. For example, if a radar transmitter is connected to port one, the antenna to port two, a microwave detector to port three, and a matched load to port four, the power received in port three is proportional to the power flowing from the transmitter to the antenna in the forward direction only. Since the reflected wave from the antenna, if it exists, is not coupled into port three, the detector monitors the power output of the transmitter.

The coupler of the present invention may also be used as the coupling device for connecting a local oscillator to a mixer circuit. For example, in a strip line balanced mixer circuit, some means must be provided for connecting the local oscillator signal to the mixer circuit. A coaxial line or waveguide type coupling obviously cannot be used in an application such as this because of the high common coupling of the coaxial line in the waveguide type with the strip line design. Therefore, in strip line balance mixing circuits, coupling devices of the type illustrated in FIG. 3 were larger than the mixer itself. With the coupler of the present invention, the benefit of small size is maintained.

While several embodiments of the invention, together with modifications thereof, have been described in detail herein and shown in the accompanying drawings, it will be evident that various further modifications are possible without departing from the scope of the invention.
What is claimed is:

1. A four-port quadrature coupler comprising:
   a plurality of strip lines in an interdigitated pattern,
   each of the four ports of the coupler integral with
   at least one of said strip lines, and
   means for interconnecting alternate strip lines in the
   interdigitated pattern.

2. A quadrature coupler as set forth in claim 1 wherein
   each strip line has an effective length equal to a quarter
   wavelength of the bandwidth center frequency.

3. A quadrature coupler as set forth in claim 1 wherein
   said interconnecting means includes multiple crossover
   wires bonded to alternate strip lines to reduce the para-
   sitic inductance.

4. A quadrature coupler comprising:
   a dielectric substrate,
   a plurality of strip lines adhesively secured to said
   dielectric substrate in an interdigitated pattern, each
   port of the coupler integral with at least one of said
   strip lines, and
   multiple crossover wires bonded to alternate strip
   lines for interconnection thereof in an interdigitated
   pattern.

5. A quadrature coupler as set forth in claim 4 wherein
   said dielectric substrate is unglazed alumina.

6. A quadrature coupler as set forth in claim 4 wherein
   each strip line has an effective length equal to a quarter
   of the wavelength of the bandwidth center frequency.

7. A quadrature coupler comprising:
   a dielectric substrate,
   a first strip line adhesively secured to said dielectric
   substrate and integral with a first port of the coupler,
   a second strip line adhesively secured to said dielectric
   substrate in an interdigitated pattern with the first
   strip line and integral with the third port of the
   coupler,
   a third strip line adhesively secured to said dielectric
   substrate in an interdigitated pattern with the first
   and second strip lines and integral with coupler ports
   two and four,
   a fourth strip line adhesively secured to said dielectric
   substrate in an interdigitated pattern with said three
   strip lines, a first section of said fourth strip line
   integral with port two of the coupler, and a second
   section of the fourth strip line integral with the port
   four of the coupler, and
   means for interconnecting alternate strip lines in the
   interdigitated pattern.

8. A quadrature coupler as set forth in claim 7 wherein
   said interconnecting means includes multiple crossover
   wires bonded to alternate strip lines to reduce parasitic
   inductance.

9. A quadrature coupler as set forth in claim 8 wherein
   said dielectric substrate is unglazed alumina.

10. A quadrature coupler as set forth in claim 9 wherein
    each strip line has a width of 4.5 mils and spaced from
    each other in an interdigitated pattern by 3.0 mils.

11. A quadrature coupler as set forth in claim 10 wherein
    said dielectric has a thickness of about 40 mils.

12. A quadrature coupler as set forth in claim 11 wherein
    each strip line has an effective length equal to a quarter
    wavelength of the bandwidth center frequency.

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