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Title: **MULTIMODE ANTENNA STRUCTURE**

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Multimode Antenna Structure

Cross Reference to Related Applications

[0001] This application claims priority from U.S. Provisional Patent Application No. 60/925,394 filed on April 20, 2007 entitled Multimode Antenna Structure, and from U.S. Provisional Patent Application No. 60/916,655 filed on May 8, 2007 also entitled Multimode Antenna Structure, both of which are hereby incorporated by reference.

BACKGROUND

Field of the Invention

[0002] The present invention relates generally to wireless communications devices and, more particularly, to antennas used in such devices.

Related Art

[0003] Many communications devices have multiple antennas that are packaged close together (e.g., less than a quarter of a wavelength apart) and that can operate simultaneously within the same frequency band. Common examples of such communications devices include portable communications products such as cellular handsets, personal digital assistants (PDAs), and wireless networking devices or data cards for personal computers (PCs). Many system architectures (such as Multiple Input Multiple Output (MIMO)) and standard protocols for mobile wireless communications devices (such as 802.11n for wireless LAN, and 3G data communications such as 802.16e (WiMAX), HSDPA, and 1xEVDO) require multiple antennas operating simultaneously.

BRIEF SUMMARY OF EMBODIMENTS OF THE INVENTION

[0004] A multimode antenna structure is provided in accordance with various embodiments of the invention for transmitting and receiving electromagnetic signals in a communications device. The communications device includes circuitry for processing signals communicated to and from the antenna structure. The antenna structure includes a plurality of antenna ports operatively coupled to the circuitry and a plurality of antenna elements, each operatively coupled to a different one of the antenna ports. The antenna structure also includes one or more connecting elements electrically connecting the antenna elements such that electrical currents on one antenna element flow to a connected neighboring antenna element and generally bypass the antenna port coupled to the neighboring antenna element, and the electrical currents flowing through the one antenna element and the neighboring antenna element are generally equal in magnitude, such that an antenna mode excited by one antenna port is generally electrically isolated from a mode excited by another antenna port at a given desired signal frequency range and the antenna elements generate diverse antenna patterns.

[0005] Various embodiments of the invention are provided in the following detailed description. As will be realized, the invention is capable of other and different embodiments, and its several details may be capable of modifications in various respects, all without departing from the invention. Accordingly, the drawings and description are to be regarded as illustrative in nature and not in a restrictive or limiting sense, with the scope of the application being indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIGURE 1A illustrates an antenna structure with two parallel dipoles.

[0007] FIGURE 1B illustrates current flow resulting from excitation of one dipole in the antenna structure of FIGURE 1A.

[0008] FIGURE 1C illustrates a model corresponding to the antenna structure of FIGURE 1A.

[0009] FIGURE 1D is a graph illustrating scattering parameters for the FIGURE 1C antenna structure.

[0010] FIGURE 1E is a graph illustrating the current ratios for the FIGURE 1C antenna structure.

[0011] FIGURE 1F is a graph illustrating gain patterns for the FIGURE 1C antenna structure.

[0012] FIGURE 1G is a graph illustrating envelope correlation for the FIGURE 1C antenna structure.

[0013] FIGURE 2A illustrates an antenna structure with two parallel dipoles connected by connecting elements in accordance with one or more embodiments of the invention.

[0014] FIGURE 2B illustrates a model corresponding to the antenna structure of FIGURE 2A.

[0015] FIGURE 2C is a graph illustrating scattering parameters for the FIGURE 2B antenna structure.

[0016] FIGURE 2D is a graph illustrating scattering parameters for the FIGURE 2B antenna structure with lumped element impedance matching at both ports.

[0017] FIGURE 2E is a graph illustrating the current ratios for the FIGURE 2B antenna structure.

[0018] FIGURE 2F is a graph illustrating gain patterns for the FIGURE 2B antenna structure.

[0019] FIGURE 2G is a graph illustrating envelope correlation for the FIGURE 2B antenna structure.

[0020] FIGURE 3A illustrates an antenna structure with two parallel dipoles connected by meandered connecting elements in accordance with one or more embodiments of the invention.

[0021] FIGURE 3B is a graph showing scattering parameters for the FIGURE 3A antenna structure.

[0022] FIGURE 3C is a graph illustrating current ratios for the FIGURE 3A antenna structure.

[0023] FIGURE 3D is a graph illustrating gain patterns for the FIGURE 3A antenna structure.

[0024] FIGURE 3E is a graph illustrating envelope correlation for the FIGURE 3A antenna structure.

[0025] FIGURE 4 illustrates an antenna structure with a ground or counterpoise in accordance with one or more embodiments of the invention.

[0026] FIGURE 5 illustrates a balanced antenna structure in accordance with one or more embodiments of the invention.

[0027] FIGURE 6A illustrates an antenna structure in accordance with one or more embodiments of the invention.

[0028] FIGURE 6B is a graph showing scattering parameters for the FIGURE 6A antenna structure for a particular dipole width dimension.

[0029] FIGURE 6C is a graph showing scattering parameters for the FIGURE 6A antenna structure for another dipole width dimension.

[0030] FIGURE 7 illustrates an antenna structure fabricated on a printed circuit board in accordance with one or more embodiments of the invention.

[0031] FIGURE 8A illustrates an antenna structure having dual resonance in accordance with one or more embodiments of the invention.

[0032] FIGURE 8B is a graph illustrating scattering parameters for the FIGURE 8A antenna structure.

[0033] FIGURE 9 illustrates a tunable antenna structure in accordance with one or more embodiments of the invention.

[0034] FIGURES 10A and 10B illustrate antenna structures having connecting elements positioned at different locations along the length of the antenna elements in accordance with one or more embodiments of the invention.

[0035] FIGURES 10C and 10D are graphs illustrating scattering parameters for the FIGURES 10A and 10B antenna structures, respectively.

[0036] FIGURE 11 illustrates an antenna structure including connecting elements having switches in accordance with one or more embodiments of the invention.

[0037] FIGURE 12 illustrates an antenna structure having a connecting element with a filter coupled thereto in accordance with one or more embodiments of the invention.

[0038] FIGURE 13 illustrates an antenna structure having two connecting elements with filters coupled thereto in accordance with one or more embodiments of the invention.

[0039] FIGURE 14 illustrates an antenna structure having a tunable connecting element in accordance with one or more embodiments of the invention.

[0040] FIGURE 15 illustrates an antenna structure mounted on a PCB assembly in accordance with one or more embodiments of the invention.

[0041] FIGURE 16 illustrates another antenna structure mounted on a PCB assembly in accordance with one or more embodiments of the invention.

[0042] FIGURE 17 illustrates an alternate antenna structure that can be mounted on a PCB assembly in accordance with one or more embodiments of the invention.

[0043] FIGURE 18A illustrates a three mode antenna structure in accordance with one or more embodiments of the invention.

[0044] FIGURE 18B is a graph illustrating the gain patterns for the FIGURE 18A antenna structure.

[0045] FIGURE 19 illustrates an antenna and power amplifier combiner application for an antenna structure in accordance with one or more embodiments of the invention.

DETAILED DESCRIPTION

[0046] In accordance with various embodiments of the invention, multimode antenna structures are provided for transmitting and receiving electromagnetic signals in communications devices. The communications devices include circuitry for processing signals communicated to and from an antenna structure. The antenna structure includes a plurality of antenna ports operatively coupled to the circuitry and a plurality of antenna elements, each operatively coupled to a different antenna port. The antenna structure also includes one or more connecting elements electrically connecting the antenna elements such that an antenna mode excited by one antenna port is generally electrically isolated from a mode excited by another antenna port at a given signal frequency range. In addition, the antenna patterns created by the ports exhibit well-defined pattern diversity with low correlation.

[0047] Antenna structures in accordance with various embodiments of the invention are particularly useful in communications devices that require multiple antennas to be packaged close together (e.g., less than a quarter of a wavelength apart), including in devices where more than one antenna is used simultaneously and particularly within the same frequency band. Common examples of such devices in which the antenna structures can be used include portable communications products such as cellular handsets, PDAs, and wireless networking devices or data cards for PCs. The antenna structures are also particularly useful with system architectures such as MIMO and standard protocols for mobile wireless communications devices (such as 802.11n for wireless LAN, and 3G data communications such as 802.16e (WiMAX), HSDPA and 1xEVDO) that require multiple antennas operating simultaneously.

[0048] FIGURES 1A-1G illustrate the operation of an antenna structure 100. FIGURE 1A schematically illustrates the antenna structure 100 having two parallel antennas, in particular parallel dipoles 102, 104, of length L. The dipoles 102, 104 are separated by a distance d, and are not connected by any connecting element. The dipoles 102, 104 have a fundamental resonant frequency that corresponds approximately to $L=\lambda/2$. Each dipole is connected to an independent transmit/receive system, which can operate at the same frequency. This system connection can have the same characteristic impedance z_0 for both antennas, which in this example is 50 ohms.

[0049] When one dipole is transmitting a signal, some of the signal being transmitted by the dipole will be coupled directly into the neighboring dipole. The maximum amount of coupling generally occurs near the half-wave resonant frequency of the individual dipole and increases as the separation distance d is made smaller. For example, for $d < \lambda/3$, the magnitude of coupling is greater than 0.1 or -10 dB, and for $d < \lambda/8$, the magnitude of the coupling is greater than -5 dB.

[0050] It is desirable to have no coupling (i.e., complete isolation) or to reduce the coupling between the antennas. If the coupling is, e.g., -10 dB, 10 percent of the transmit power is lost due to that amount of power being directly coupled into the neighboring antenna. There may also be detrimental system effects such as saturation or desensitization of a receiver connected to the neighboring antenna or degradation of the performance of a transmitter connected to the neighboring antenna. Currents induced on the neighboring antenna distort the gain pattern compared to that generated by an individual dipole. This effect is known to reduce the correlation between the gain patterns produced by the dipoles. Thus, while coupling may provide some pattern diversity, it has detrimental system impacts as described above.

[0051] Because of the close coupling, the antennas do not act independently and can be considered an antenna system having two pairs of terminals or ports that correspond to two different gain patterns. Use of either port involves substantially the entire structure including both dipoles. The parasitic excitation of the neighboring dipole enables diversity to be achieved at close dipole spacing, but currents excited on the dipole pass through the source impedance, and therefore manifest mutual coupling between ports.

[0052] FIGURE 1C illustrates a model dipole pair corresponding to the antenna structure 100 shown in FIGURE 1 used for simulations. In this example, the dipoles 102, 104 have a square cross section of 1 mm x 1 mm and length (L) of 56 mm. These dimensions yield a center resonant frequency of 2.45 GHz when attached to a 50-ohm source. The free-space wavelength at this frequency is 122 mm. A plot of the scattering parameters S11 and S12 for a separation distance (d) of 10 mm, or approximately λ/12, is shown in FIGURE 1D. Due to symmetry and reciprocity, S22=S11 and S12=S21. For simplicity, only S11 and S12 are shown and discussed. In this configuration, the coupling between dipoles as represented by S12 reaches a maximum of -3.7 dB.

[0053] FIGURE 1E shows the ratio (identified as “Magnitude I2/I1” in the figure) of the vertical current on dipole 104 of the antenna structure to that on dipole 102 under the condition in which port 106 is excited and port 108 is passively terminated. The frequency at which the ratio of currents (dipole 104/dipole 102) is a maximum corresponds to the frequency of 180 degree phase differential between the dipole currents and is just slightly higher in frequency than the point of maximum coupling shown in FIGURE 1D.

[0054] FIGURE 1F shows azimuthal gain patterns for several frequencies with excitation of port 106. The patterns are not uniformly omni-directional and change with frequency due to the changing magnitude and phase of the coupling. Due to symmetry, the patterns resulting from excitation of port 108 would be the mirror image of those for port 106. Therefore, the more asymmetrical the pattern is from left to right, the more diverse the patterns are in terms of gain magnitude.

[0055] Calculation of the correlation coefficient between patterns provides a quantitative characterization of the pattern diversity. FIGURE 1G shows the calculated correlation between port 106 and port 108 antenna patterns. The correlation is much lower than is predicted by Clark’s model for ideal dipoles. This is due to the differences in the patterns introduced by the mutual coupling.

[0056] FIGURES 2A-2F illustrate the operation of an exemplary two port antenna structure 200 in accordance with one or more embodiments of the invention. The two port antenna structure 200 includes two closely-spaced resonant antenna elements 202, 204 and provides both low pattern correlation and low coupling between ports 206, 208. FIGURE 2A schematically illustrates the two port antenna structure 200. This structure is similar to the antenna structure 100 comprising the pair of dipoles shown in FIGURE 1B, but additionally includes horizontal conductive connecting elements 210, 212 between the dipoles on either side of the ports 206, 208. The two ports 206, 208 are located in the same locations as with the FIGURE 1 antenna structure. When one port is excited, the combined structure exhibits a resonance similar to that of the unattached pair of dipoles, but with a significant reduction in coupling and an increase in pattern diversity.

[0057] An exemplary model of the antenna structure 200 with a 10 mm dipole separation is shown in FIGURE 2B. This structure has generally the same geometry as the antenna structure 100 shown in FIGURE 1C, but with the addition of the two horizontal connecting elements 210, 212 electrically connecting the antenna elements slightly above and below the ports. This structure shows a strong resonance at the same frequency as unattached dipoles, but with very different scattering parameters as shown in FIGURE 2C. There is a deep drop-out in coupling, below -20 dB, and a shift in the input impedance as indicated by S11. In this example, the best impedance match (S11 minimum) does not coincide with the lowest coupling (S12 minimum). A matching network can be used to improve the input impedance match and still achieve very low coupling as shown in FIGURE 2D. In this example, a lumped element matching network comprising a series inductor followed by a shunt capacitor was added between each port and the structure.

[0058] FIGURE 2E shows the ratio (indicated as “Magnitude I2/I1” in the figure) of the current on dipole element 204 to that on dipole element 202 resulting from excitation of port 206. This plot shows that below the resonant frequency, the currents are actually greater on dipole element 204. Near resonance, the currents on dipole element 204 begin to decrease relative to those on dipole element 202 with increasing frequency. The point of minimum coupling (2.44 GHz in this case) occurs near the frequency where currents on both dipole elements are generally equal in magnitude. At this frequency, the phase of the currents on dipole element 204 lag those of dipole element 202 by approximately 160 degrees.

[0059] Unlike the FIGURE 1C dipoles without connecting elements, the currents on antenna element 204 of the FIGURE 2B combined antenna structure 200 are not forced to pass through the terminal impedance of port 208. Instead a resonant mode is produced where the current flows down antenna element 204, across the connecting element 210, 212, and up antenna element 202 as indicated by the arrows shown on FIGURE 2A. (Note that this current flow is representative of one half of the resonant cycle; during the other half, the current directions are reversed). The resonant mode of the combined structure features the following: (1) the currents on antenna element 204 largely bypass port 208, thereby allowing for high isolation between the ports 206, 208, and (2) the magnitude of the currents on both antenna elements 202,204 are approximately equal, which allows for dissimilar and uncorrelated gain patterns as described in further detail below.

[0060] Because the magnitude of currents is nearly equal on the antenna elements, a much more directional pattern is produced (as shown on FIGURE 2F) than in the case of the FIGURE 1C antenna structure 100 with unattached dipoles. When the currents are equal, the condition for nulling the pattern in the x (or phi=0) direction is for the phase of currents on dipole 204 to lag those of dipole 202 by the quantity π-kd (where $k=2\pi/\lambda$, and λ is the effective wavelength). Under this condition, fields propagating in the phi=0 direction from dipole 204 will be 180 degrees out of phase with those of dipole 202, and the combination of the two will therefore have a null in the phi=0 direction.

[0061] In the model example of FIGURE 2B, d is 10 mm or an effective electrical length of $\lambda/12$. In this case, kd equates $\pi/6$ or 30 degrees, and so the condition for a directional azimuthal radiation pattern with a null towards phi=0 and maximum gain towards phi=180 is for the current on dipole 204 to lag those on dipole 202 by 150 degrees. At resonance, the currents pass close to this condition (as shown in FIGURE 2E), which explains the directionality of the patterns. In the case of the excitation of port 204, the radiation patterns are the mirror opposite of those of FIGURE 2F, and maximum gain is in the phi=0 direction. The difference in antenna patterns produced from the two ports has an associated low predicted envelope correlation as shown on FIGURE 2G. Thus the combined antenna structure has two ports that are isolated from each other and produce gain patterns of low correlation.

[0062] Accordingly, the frequency response of the coupling is dependent on the characteristics of the connecting elements 210, 212, including their impedance and electrical length. In accordance with one or more embodiments of the invention, the frequency or bandwidth over which a desired amount of isolation can be maintained is controlled by appropriately configuring the connecting elements. One way to configure the cross connection is to change the physical length of the connecting element. An example of this is shown by the multimode antenna structure 300 of FIGURE 3A where a meander has been added to the cross connection path of the connecting elements 310, 312. This has the general effect of increasing both the electrical length and the impedance of the connection between the two antenna elements

302, 304. Performance characteristics of this structure including scattering parameters, current ratios, gain patterns, and pattern correlation are shown on FIGURES 3B, 3C, 3D, and 3E, respectively. In this embodiment, the change in physical length has not significantly altered the resonant frequency of the structure, but there is a significant change in S12, with larger bandwidth and a greater minimum value than in structures without the meander. Thus, it is possible to optimize or improve the isolation performance by altering the electrical characteristic of the connecting elements.

[0063] Exemplary multimode antenna structures in accordance with various embodiments of the invention can be designed to be excited from a ground or counterpoise 402 (as shown by antenna structure 400 in FIGURE 4), or as a balanced structure (as shown by antenna structure 500 in FIGURE 5). In either case, each antenna structure includes two or more antenna elements (402, 404 in FIGURE 4, and 502, 504 in FIGURE 5) and one or more electrically conductive connecting elements (406 in FIGURE 4, and 506, 508 in FIGURE 5). For ease of illustration, only a two-port structure is illustrated in the example diagrams. However, it is possible to extend the structure to include more than two ports in accordance with various embodiments of the invention. A signal connection to the antenna structure, or port (418, 412 in FIGURE 4 and 510, 512 in FIGURE 5), is provided at each antenna element. The connecting element provides electrical connection between the two antenna elements at the frequency or frequency range of interest. Although the antenna is physically and electrically one structure, its operation can be explained by considering it as two independent antennas. For antenna structures not including a connecting element such as antenna structure 100, port 106 of that structure can be said to be connected to antenna 102, and port 108 can be said to be connected to antenna 104. However, in the case of this combined structure such as antenna structure 400, port 418 can be referred to as being associated with one antenna mode, and port 412 can be referred to as being associated with another antenna mode.

[0064] The antenna elements are designed to be resonant at the desired frequency or frequency range of operation. The lowest order resonance occurs when an antenna element has an electrical length of one quarter of a wavelength. Thus, a simple element design is a quarter-wave monopole in the case of an unbalanced configuration. It is also possible to use higher order modes. For example, a structure formed from quarter-wave monopoles also exhibits dual mode antenna performance with high isolation at a frequency of three times the fundamental frequency. Thus, higher order modes may be exploited to create a multiband antenna. Similarly, in a balanced configuration, the antenna elements can be complementary quarter-wave elements as in a half-wave center-fed dipole. However, the antenna structure can also be formed from other types of antenna elements that are resonant at the desired frequency or frequency range. Other possible antenna element configurations include, but are not limited to, helical coils, wideband planar shapes, chip antennas, meandered shapes, loops, and inductively shunted forms such as Planar Inverted-F Antennas (PIFAs).

[0065] The antenna elements of an antenna structure in accordance with one or more embodiments of the invention need not have the same geometry or be the same type of antenna element. The antenna elements should each have resonance at the desired frequency or frequency range of operation.

[0066] In accordance with one or more embodiments of the invention, the antenna elements of an antenna structure have the same geometry. This is generally desirable for design simplicity, especially when the antenna performance requirements are the same for connection to either port.

[0067] The bandwidth and resonant frequencies of the combined antenna structure can be controlled by the bandwidth and resonance frequencies of the antenna elements. Thus, broader bandwidth elements can be used to produce a broader bandwidth for the modes of the combined structure as illustrated, e.g., in FIGURES 6A, 6B, and 6C. FIGURE 6A illustrates a multimode antenna structure 600 including two dipoles 602, 604 connected by connecting elements 606, 608. The dipoles 602, 604 each have a width (W) and a length (L) and are spaced apart by a distance (d). FIGURE 6B illustrates the scattering parameters for the structure having exemplary dimensions: W= 1 mm, L=57.2 mm, and d=10mm. FIGURE 6C illustrates the scattering parameters for the structure having exemplary dimensions: W= 10 mm, L=50.4 mm, and d=10mm. As shown, increasing W from 1 mm to 10 mm, while keeping the other dimensions generally the same, results in a broader isolation bandwidth and impedance bandwidth for the antenna structure.

[0068] It has also been found that increasing the separation between the antenna elements increases the isolation bandwidth and the impedance bandwidth for an antenna structure.

[0069] In general, the connecting element is in the high-current region of the combined resonant structure. It is therefore preferable for the connecting element to have a high conductivity.

[0070] The ports are located at the feed points of the antenna elements as they would be if they were operated as separate antennas. Matching elements or structures may be used to match the port impedance to the desired system impedance.

[0071] In accordance with one or more embodiments of the invention, the multimode antenna structure can be a planar structure incorporated, e.g., into a printed circuit board, as shown as FIGURE 7. In this example, the antenna structure 700 includes antenna elements 702, 704 connected by a connecting element 706 at ports 708, 710. The antenna structure is fabricated on a printed circuit board substrate 712. The antenna elements shown in the figure are simple quarter-wave monopoles. However, the antenna elements can be any geometry that yields an equivalent effective electrical length.

[0072] In accordance with one or more embodiments of the invention, antenna elements with dual resonant frequencies can be used to produce a combined antenna structure with dual resonant frequencies and hence dual operating frequencies. FIGURE 8A shows an exemplary model of a multimode dipole structure 800 where the dipole antenna elements 802, 804 are split into two fingers 806, 808 and 810, 812, respectively, of unequal length. The dipole antenna elements have resonant frequencies associated with each the two different finger lengths and accordingly exhibit a dual resonance. Similarly, the multimode antenna structure using dual-resonant dipole arms exhibits two frequency bands where high isolation (or small S21) is obtained as shown in FIGURE 8B.

[0073] In accordance with one or more embodiments of the invention, a multimode antenna structure 900 shown in FIGURE 9 is provided having variable length antenna elements 902, 904 forming a tunable antenna. This may be done by changing the effective electrical length of the antenna elements by a controllable device such as an RF switch 906, 908 at each antenna element 902, 904. In this example, the switch may be opened (by operating the controllable device) to create a shorter electrical length (for higher frequency operation) or closed to create a longer electrical length (for lower frequency of operation). The operating frequency band for the antenna structure 900, including the feature of high isolation, can be tuned by tuning both antenna elements in concert. This approach may be used with a variety of methods of changing the effective electrical length of the antenna elements including, e.g., using a controllable dielectric material, loading the antenna elements with a variable capacitor such as a MEMs device, varactor, or tunable dielectric capacitor, and switching on or off parasitic elements.

[0074] In accordance with one or more embodiments of the invention, the connecting element or elements provide an electrical connection between the antenna elements with an electrical length approximately equal to the electrical distance between the elements. Under this condition, and when the connecting elements are attached at the port ends of the antenna elements, the ports are isolated at a frequency near the resonance frequency of the antenna elements. This arrangement can produce nearly perfect isolation at particular frequency.

[0075] Alternately, as previously discussed, the electrical length of the connecting element may be increased to expand the bandwidth over which isolation exceeds a particular value. For example, a straight connection between antenna elements may produce a minimum S21 of -25 dB at a particular frequency and the bandwidth for which S21 < -10 dB may be 100 MHz. By increasing the electrical length, a new response can be obtained where the minimum S21 is increased to -15 dB but the bandwidth for which S21 < -10 dB may be increased to 150 MHz.

[0076] Various other multimode antenna structures in accordance with one or more embodiments of the invention are possible. For example, the connecting element can have a varied geometry or can be constructed to include components to vary the properties of the antenna structure. These components can include, e.g., passive inductor and capacitor elements, resonator or filter structures, or active components such as phase shifters.

[0077] In accordance with one or more embodiments of the invention, the position of the connecting element along the length of the antenna elements can be varied to adjust the properties of the antenna structure. The frequency band over which the ports are isolated can be shifted upward in frequency by moving the point of attachment of the connecting element on the antenna elements away from the ports and towards the distal end of the antenna elements. FIGURES 10A and 10B illustrate multimode antenna structures 1000, 1002, respectively, each having a connecting element electrically connected to the antenna elements. In the FIGURE

10A antenna structure 1000, the connecting element 1004 is located in the structure such the gap between the connecting element 1004 and the top edge of the ground plane 1006 is 3 mm. FIGURE 10C shows the scattering parameters for the structure showing that high isolation is obtained at a frequency of 1.15 GHz in this configuration. A shunt capacitor/series inductor matching network is used to provide the impedance match at 1.15 GHz. FIGURE 10D shows the scattering parameters for the structure 1002 of FIGURE 10B, where the gap between the connecting element 1008 and the top edge 1010 of the ground plane is 19 mm. The antenna structure 1002 of FIGURE 10B exhibits an operating band with high isolation at approximately 1.50 GHz.

[0078] FIGURE 11 schematically illustrates a multimode antenna structure 1100 in accordance with one or more further embodiments of the invention. The antenna structure 1100 includes two or more connecting elements 1102, 1104, each of which electrically connects the antenna elements 1106, 1108. (For ease of illustration, only two connecting elements are shown in the figure. It should be understood that use of more than two connecting elements is also contemplated.) The connecting elements 1102, 1104 are spaced apart from each other along the antenna elements 1106, 1108. Each of the connecting elements 1102, 1104 includes a switch 1112, 1110. Peak isolation frequencies can be selected by controlling the switches 1110, 1112. For example, a frequency f1 can be selected by closing switch 1110 and opening switch 1112. A different frequency f2 can be selected by closing switch 1112 and opening switch 1110.

[0079] FIGURE 12 illustrates a multimode antenna structure 1200 in accordance with one or more alternate embodiments of the invention. The antenna structure 1200 includes a connecting element 1202 having a filter 1204 operatively coupled thereto. The filter 1204 can be a low pass or band pass filter selected such that the connecting element connection between the antenna elements 1206, 1208 is only effective within the desired frequency band, such as the high isolation resonance frequency. At higher frequencies, the structure will function as two separate antenna elements that are not coupled by the electrically conductive connecting element, which is open circuited.

[0080] FIGURE 13 illustrates a multimode antenna structure 1300 in accordance with one or more alternate embodiments of the invention. The antenna structure 1300 includes two or more connecting elements 1302, 1304, which include filters 1306, 1308, respectively. (For ease of illustration, only two connecting elements are shown in the figure. It should be understood that use of more than two connecting elements is also contemplated.) In one possible embodiment, the antenna structure 1300 has a low pass filter 1308 on the connecting element 1304 (which is closer to the antenna ports) and a high pass filter 1306 on the connecting element 1302 in order to create an antenna structure with two frequency bands of high isolation, i.e., a dual band structure.

[0081] FIGURE 14 illustrates a multimode antenna structure 1400 in accordance with one or more alternate embodiments of the invention. The antenna structure 1400 includes one or more connecting elements 1402 having a tunable element 1406 operatively connected thereto. The antenna structure 1400 also includes antenna elements 1408, 1410. The tunable element 1406 alters the delay or phase of the electrical connection or changes the reactive impedance of the electrical connection. The magnitude of the scattering parameters S21/S12 and a frequency response are affected by the change in electrical delay or impedance and so an antenna structure can be adapted or generally optimized for isolation at specific frequencies using the tunable element 1406.

[0082] FIGURE 15 illustrates a multimode antenna structure 1500 in accordance with one or more alternate embodiments of the invention. The multimode antenna structure 1500 can be used, e.g., in a WIMAX USB dongle. The antenna structure 1500 can be configured for operation, e.g., in WiMAX bands from 2300 to 2700 MHz.

[0083] The antenna structure 1500 includes two antenna elements 1502, 1504 connected by a conductive connecting element 1506. The antenna elements include slots to increase the electrical length of the elements to obtain the desired operating frequency range. In this example, the antenna structure is optimized for a center frequency of 2350 MHz. The length of the slots can be reduced to obtain higher center frequencies. The antenna structure is mounted on a printed circuit board assembly 1508. A two-component lumped element match is provided at each antenna feed.

[0084] The antenna structure 1500 can be manufactured, e.g., by metal stamping. It can be made, e.g., from 0.2 mm thick copper alloy sheet. The antenna structure 1500 includes a pickup feature 1510 on the connecting element at the center of mass of the structure, which can be used in an automated pick-and-place assembly process. The antenna structure is also compatible with surface-mount reflow assembly.

[0085] FIGURE 16 illustrates a multimode antenna structure 1600 in accordance with one or more alternate embodiments of the invention. As with antenna structure 1500 of FIGURE 15, the antenna structure 1600 can also be used, e.g., in a WIMAX USB dongle. The antenna structure can be configured for operation, e.g., in WiMAX bands from 2300 to 2700 MHz.

[0086] The antenna structure 1600 includes two antenna elements 1602, 1604, each comprising a meandered monopole. The length of the meander determines the center frequency. The exemplary design shown in the figure is optimized for a center frequency of 2350 MHz. To obtain higher center frequencies, the length of the meander can be reduced.

[0087] A connecting element 1606 electrically connects the antenna elements. A two-component lumped element match is provided at each antenna feed.

[0088] The antenna structure can be fabricated, e.g., from copper as a flexible printed circuit (FPC) mounted on a plastic carrier 1608. The antenna structure can be created by the metalized portions of the FPC. The plastic carrier provides mechanical support and facilitates mounting to a PCB assembly 1610. Alternatively, the antenna structure can be formed from sheet-metal.

[0089] FIGURE 17 illustrates a multimode antenna structure 1700 in accordance with another embodiment of the invention. This antenna design can be used, e.g., for USB, Express 34, and Express 54 data card formats. The exemplary antenna structure shown in the figure is designed to operate at frequencies from 2.3 to 6 GHz. The antenna structure can be fabricated, e.g., from sheet-metal or by FPC over a plastic carrier 1702.

[0090] FIGURE 18A illustrates a multimode antenna structure 1800 in accordance with another embodiment of the invention. The antenna structure 1800 comprises a three mode antenna with three ports. In this structure, three monopole antenna elements 1802, 1804, 1806 are connected using a connecting element 1808 comprising a conductive ring that connects neighboring antenna elements. The antenna elements are balanced by a common counterpoise, or sleeve 1810, which is a single hollow conductive cylinder. The antenna has three coaxial cables 1812, 1814, 1816 for connection of the antenna structure to a communications device. The coaxial cables 1812, 1814, 1816 pass through the hollow interior of the sleeve 1810. The antenna assembly may be constructed from a single flexible printed circuit wrapped into a cylinder and may be packaged in a cylindrical plastic enclosure to provide a single antenna assembly that takes the place of three separate antennas. In one exemplary arrangement, the diameter of the cylinder is 10 mm and the overall length of the antenna is 56 mm so as to operate with high isolation between ports at 2.45 GHz. This antenna structure can be used, e.g., with multiple antenna radio systems such as MIMO or 802.11N systems operating in the 2.4 to 2.5 GHz bands. In addition to port to port isolation, each port advantageously produces a different gain pattern as shown on FIGURE 18B. While this is one specific example, it is understood that this structure can be scaled to operate at any desired frequency. It is also understood that methods for tuning, manipulating bandwidth, and creating multiband structures described previously in the context of two-port antennas can also apply to this multiport structure.

[0091] While the above embodiment is shown as a true cylinder, it is possible to use other arrangements of three antenna elements and connecting elements that produce the same advantages. This includes, but is not limited to, arrangements with straight connections such that the connecting elements form a triangle, or another polygonal geometry. It is also possible to construct a similar structure by similarly connecting three separate dipole elements instead of three monopole elements with a common counterpoise. Also, while symmetric arrangement of antenna elements advantageously produces equivalent performance from each port, e.g., same bandwidth, isolation, impedance matching, it is also possible to arrange the antenna elements asymmetrically or with unequal spacing depending on the application.

[0092] FIGURE 19 illustrates use of a multimode antenna structure 1900 in a combiner application in accordance with one or more embodiments of the invention. As shown in the figure, transmit signals may be applied to both antenna ports of the antenna structure 1900 simultaneously. In this configuration, the multimode antenna can serve as both antenna and power amplifier combiner. The high isolation between antenna ports restricts interaction between the two amplifiers 1902, 1904, which is known to have undesirable effects such as signal distortion and loss of efficiency. Optional impedance matching at 1906 can be provided at the antenna ports.

[0093] It is to be understood that although the invention has been described above in terms of particular embodiments, the foregoing embodiments are provided as illustrative only, and do not limit or define the scope of the invention.

[0094] Various other embodiments, including but not limited to the following, are also within the scope of the claims. For example, the elements or components of the various multimode antenna structures described herein may be further divided into additional components or joined together to form fewer components for performing the same functions. For example, the antenna elements and the connecting element or elements that are part of a multimode antenna structure may be combined to form a single radiating structure having multiple feed points operatively coupled to a plurality of antenna ports.

[0095] Having described preferred embodiments of the present invention, it should be apparent that modifications can be made without departing from the spirit and scope of the invention.

[0096] What is claimed is: