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Multiband hybrid loop-notch antennas

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Abstract: The study describes a small antenna with a hybrid loop-notch configuration. This format has very small dimensions in terms of the operating wavelength and operation is possible over two or more non-contiguous frequency bands. When integrated into a host circuit board it can be designed to maintain a substantially constant resonant frequency in the presence of obstructions such as the human body. A number of different simple feed arrangements are described, which can be adapted to suit other implementations.

1 Introduction

Requirements for small wireless-connected devices continue to drive the need for antennas that are both efficient and physically compact. The dependence of the bandwidth of an electrically small antenna on the dimensions of the platform on which it is mounted is described in [1–3]. The most commonly used antennas on small platforms have been bent or meandered monopoles and inverted-F antennas, mounted at the end of the platform, which excite the characteristic modes. The hybrid loop-notch antenna provides a simple and easily optimised alternative to more usual antenna formats. When optimised it can provide greater bandwidth, smaller occupied area and reduced de-tuning in the presence of the human body. This paper, an expanded version of [4], describes implementations for the single band and multi-frequency operation.

The wide bandwidth and high efficiency of the loop-notch, notwithstanding its small electrical dimensions, make it obvious that it is the size of the platform that limits these parameters rather than the dimensions of the antenna itself. The loop-notch is most effective when positioned mid-way along a long edge of a small platform. Electrically small end-mounted magnetic dipoles [5] and isolated ‘islands’ have also been used to drive ground plane currents; examples of these include a UHF-TV antenna [6] and a multiband WWAN antenna [7].

The purpose of this paper is to stimulate further investigation of the possibilities of electrically very small antennas that operate in conjunction with conductive ground planes, a combination of great practical value. In the configurations described, classical bandwidth/efficiency performance limits apply to the dimensions of the ground plane, but it is not obvious which limits apply to the structure (the ‘antenna’) that excites it.

All the example antennas described in this paper were made on 0.8 mm thick FR4-class substrate (Isola 470HR). All gain, pattern and efficiency results were measured using a Satimo Stargate-64 chamber; impedances were measured using Agilent 8714ET or Anritsu MS2035B vector network analysers. For all measurements, feed cable was fitted with a quarter-wave sleeve choke.

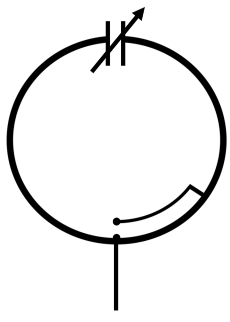


Fig. 1 *Typical loop with tapped feed*

2 Loops and notches

The classical loop antenna comprises a single turn closed circular loop [8]. The radiation resistance of such a loop is very small if its dimensions are small compared with the wavelength, so an auxiliary smaller coupling loop is usually placed within the main loop to form an impedance transformer. The outer loop is tuned to resonate at the wanted frequency by a series capacitor and the dimensions of the coupling loop are chosen to provide a match at resonance to a 50 Ω source. The feed loop may be independent of the main loop or may be tapped onto it (as shown in Fig. 1), but for an electrically small loop the resonance is sharp and the impedance bandwidth that can be achieved is very narrow. The radiation pattern of an electrically small loop antenna is similar to that of a dipole, oriented with the nulls directed at right angles to the plane of the loop.

Notch antennas (Fig. 2) derive from open-circuit slots and are fed by applying a voltage between the sides of the notch. They have been used on aircraft, and are usually tuned using a capacitor placed across (or close to) the open end [9, 10]. The notch is related to the Vivaldi antenna but is electrically much smaller and its radiation relies on exciting currents in its host ground plane.

3 Hybrid loop-notch

3.1 Single notch design

In the present context, the hybrid loop-notch comprises a small aperture, placed close to the edge of a ground with an opening in the edge of the ground plane. The antenna is simple to realise in printed circuit form and is easily integrated with a microstrip feedline. It owes its small size and wide bandwidth to the fact that the notch is an effective driver of radiating currents in the host platform. The term *notch antenna* has recently been used of a patch antenna with an embedded open-circuit half-slot [11], but this is not consistent with long-established use of the terminology.

The basic format of the loop-notch antenna is shown in Fig. 3*a*. The resonant frequency of the antenna is determined by the inductance of the path around the aperture together with the capacitance across the opening. The notch may be excited by an input line passing directly across part of the main opening (Fig. 3*a*) or by a loop in the feed line lying within the main aperture (Fig. 3*b*). The resistive component of the input impedance at

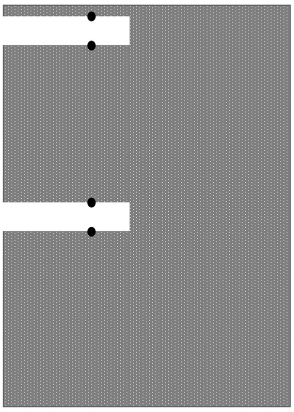
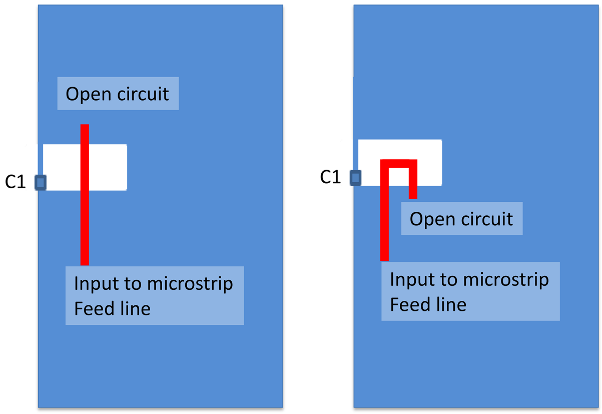


Fig. 2 *Notches, showing positions in the centre and near the edge of a host PCB*



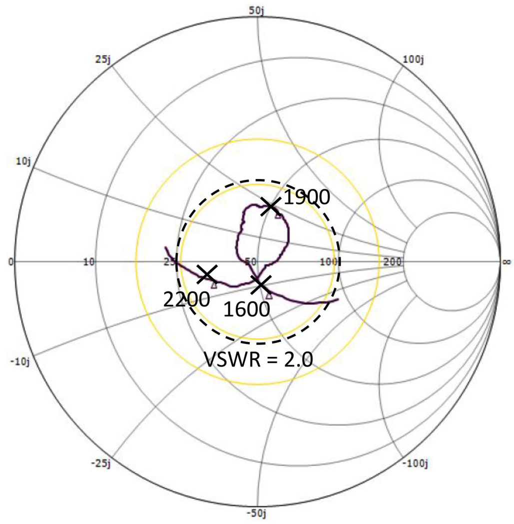
a *b*

Fig. 3 *Alternative configurations for a loop-notch antenna*
(a) Direct feed by a microstrip line passing across a loop-notch, ***(b)*** Indirect feed using a separate inner loop

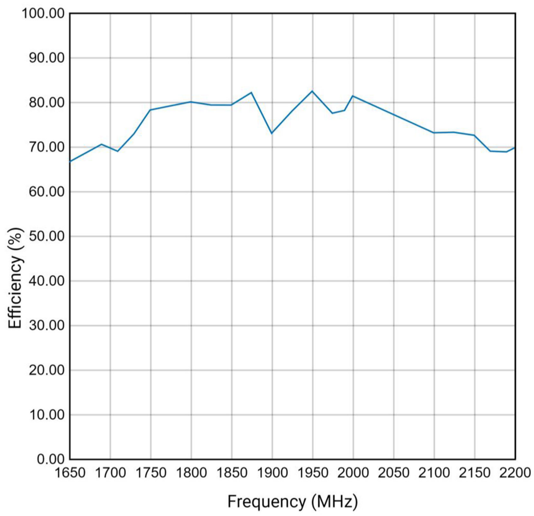
resonance is determined by the degree of coupling provided by the geometry of the feed line. For a straight feedline the controlling parameter is the ratio of the area between the feedline and the short-circuit end of the aperture, compared with the area of the whole aperture. Input matching is optimised by placing a capacitive reactance in series with the feed line. This may be provided by a chip capacitor or may be formed by extending the feed line over the underlying ground plane, forming a series capacitive stub as shown in Figs. 3*a* and *b*. The use of a chip capacitor provides a slightly more compact arrangement than an open circuit microstrip stub. The required value of capacitance is a function of the electrical dimensions of the notch and the ground plane, together with the position of the notch along the edge of the ground plane; it is easily determined by simulation or experiment. In some realisations, the tuning capacitance C1 may have a very small value, and can be provided by a copper tab located on the opposite face of the PCB, overlapping the opening of the notch. While no matching network is necessary, it may be convenient to allow for one, making it easy to re-centre the impedance plot if there is a difference between prototype and production environments.

In a practical example using a straight microstrip feed (as in shown Fig. 3*a*), a rectangular notch 4 mm wide and 10.5 mm long was placed half way along the long edge of a 60 mm × 40 mm ground plane This provided the measured impedance and efficiency shown in Figs. 4*a* and *b*. The importance of the ground plane dimensions is illustrated by comparing Fig. 4*a* with Fig. 5, in which a notch of the same dimensions was placed at the midpoint of the short edge of the same ground plane.

Related designs have been described in [12], and in [13] which also describes dual-band operation, but both these earlier designs are significantly larger than the present configurations.



a



b

Fig. 4 *Measured performance of a 4 mm × 10.5 mm notch, half way along the long edge of a 60 mm × 40 mm ground plane*
(a) Impedance and, ***(b)*** Efficiency

3.1.1 Characteristic modes: The ability of the electrically very small structure of the loop-notch to provide wide bandwidth and high efficiency derives from its excitation of characteristic modes in the ground plane of the host platform. These have been well described [1–3] and are relied on by any small antenna that is required to provide efficiency and bandwidth exceeding the classical Chu-Harrington limit [14–16] as it relates to the antenna itself.

All unbalanced electrically small antennas rely for their bandwidth on currents induced in the ground plane. Inverted-F antennas, bent monopoles and their meandered, tapped and branched derivatives all have radiating elements that create high *E* fields; and provide the greatest efficiency and bandwidth when these fields align with the axis of a ground plane whose electrical length exceeds around 0.3λ. By contrast, the loop-notch acts as a low-impedance current generator and is most effective when placed at a low impedance point along the edge of the ground plane.

Perhaps the most surprising feature of the loop-notch antenna is the effectiveness of the coupling that can be provided by a very small notch between currents around the notch and those excited in the whole ground plane. In the example of Figs. 4 and 5, the ground plane is 60 mm long and 40 mm wide (0.39λ□0.25λ at mid band) but the notch dimensions are only 4 mm × 10.5 mm ($0.026\lambda \times 0.071\lambda$). The loop in the input impedance plot could have been made smaller by reducing the coupling to the notch (moving the

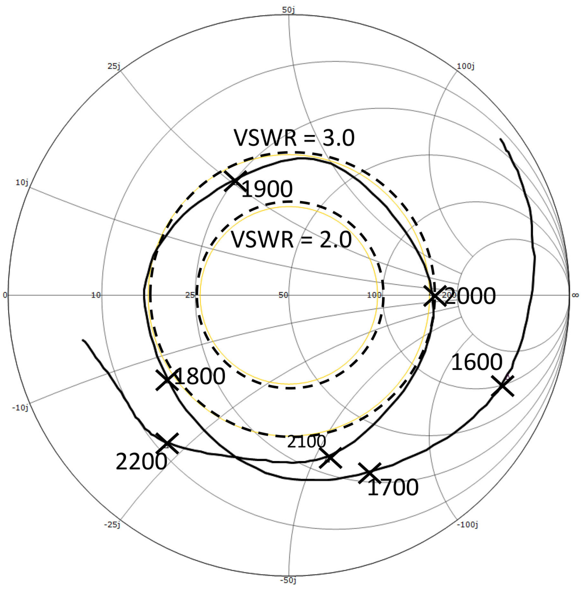


Fig. 5 *Impedance plot of a notch of the same dimensions as that in Fig. 4, but placed in the short edge of the 60 mm × 40 mm ground plane*

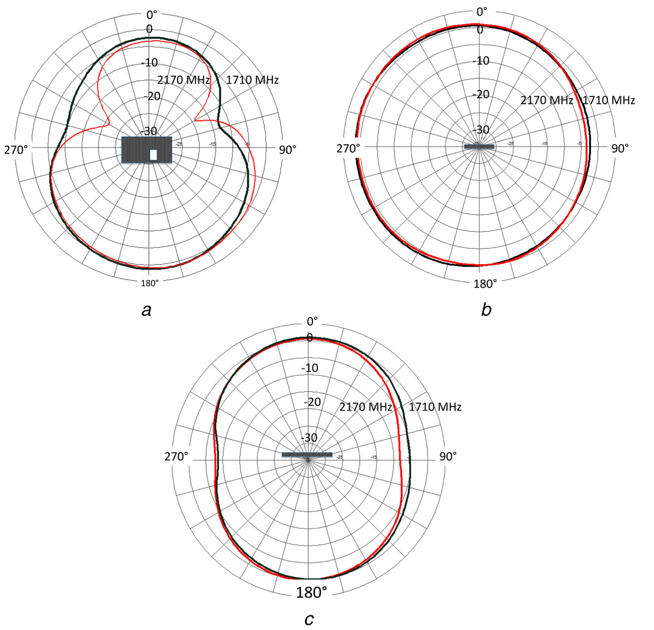


Fig. 6 *Radiation patterns of 4 mm × 10.5 mm notch in 60 mm × 40 mm ground plane. Radial scale is dBi*
(a) *X–Y* plane, ***(b)*** *Y–Z* plane, ***(c)*** *X–Z* plane

feed line away from the open edge), but a diminished bandwidth would have resulted.

3.1.2 Radiation patterns: The radiation patterns the loop-notch of Figs. 4 and 5 at 1710 and 2170 MHz are shown in Fig. 6. These are similar to those of a half-wave dipole, but the nulls are displaced from the axis of the ground plane and the nulls are reduced in depth. Both these effects are to be expected because of the asymmetry of the excitation of the ground plane.

The radiation patterns of most embedded loop-notches in electrically small ground planes are generally very similar to those in Fig. 6 where the ground plane was 0.4λ long at at mid band, but in a larger ground plane the excited characteristic modes will have multiple nodes and antinodes. In this case, the radiation pattern will be more complex, and will more strongly depend on the electrical size of the ground plane and the location of the antenna. A classical small loop has a null in its radiation pattern in the plane of the loop, but this is not found in the pattern of the embedded loop-notch because the radiation pattern is dominated by the effect of currents in the ground plane.

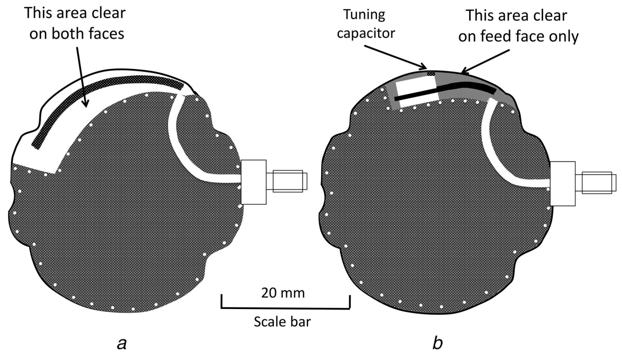


Fig. 7 *PCB for a wrist-worn device with alternative bent monopole and notch antenna*

3.1.3 Printed circuit board (PCB) design: The design of any RF PCB with an integrated antenna of any design must provide for the flow of the characteristic mode currents across its whole surface, irrespective of the choice of antenna type. A good RF PCB design has a ground flood on both external faces, stitched together with closely spaced vias around the edges of the board, as seen in Fig. 7. The layout of all components must take account of the RF currents that flow on the external surfaces, avoiding long interruptions in the ground plane at right angles to the direction of current flow, and using screening cans to enable current flow over major disruptions within the ground plane. This design principle applies to both transmission and reception: a design for high receiver sensitivity relies on avoiding the creation of noise currents on the outer faces of the PCB and the fitting of screening cans over any noisy components (including processors, clocks, memory and switch-mode poser supplies). This form of design, keeping all noisy circuit traces within the screened enclosure provided by the external ground planes, aligns well with a design for optimum electromagnetic compatibility performance.

3.1.4 Detuning: Detuning is often described by the change in the frequency of optimum matching when an antenna, or a device containing an antenna, is brought close to another object or to the human body, for example when a device is held in the hand or close to the head. The capacitance between the antenna and the body typically causes the resonant frequency of a planar inverted-F antenna (PIFA) or a monopole to fall relative to that in free space [17]. By contrast, the inductance of a loop falls when approached by a conductive object [18] causing its resonant frequency to rise. In this respect, if the tuning capacitance of a loop-notch is large it behaves like a loop; if it is small, it behaves like a PIFA. By selecting the antenna dimensions and the degree of capacitive tuning, it is possible to avoid any significant change of resonant frequency as the platform approaches the body. The input impedance of the antenna will change because of reflection and absorption by the body, but its optimum match and gain remains at the same frequency (as shown in Fig. 8).

3.2 Dual-band notches

For many modern applications, it is required that antennas operate on two or more non-contiguous frequency bands. While it is relatively easy to provide operation on the third harmonic of the fundamental resonant frequency of many antennas – including dipoles, monopoles and PIFAs, – it is less easy to provide for operation on the second harmonic, as required for example for many multi-band cellular and dual-band WiFi applications.

For some frequency relationships it is possible to obtain dual-band operation from a single notch, Dual loop-notches, as shown in Figs. 9 and 10, can provide another solution to this practical requirement. Here two notches are positioned close together along one edge of the host PCB; a single feedline crosses them both and is terminated by a fixed capacitor or stub.

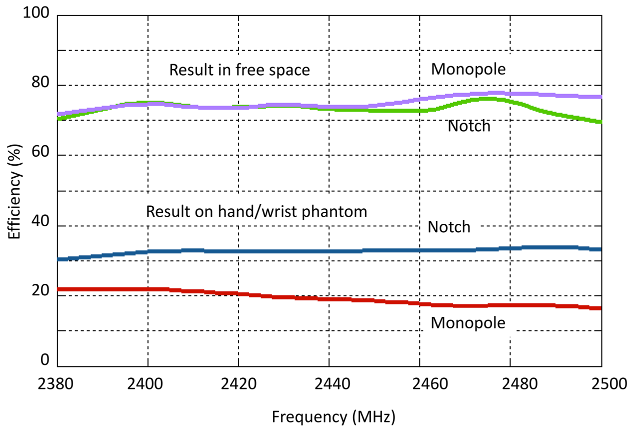


Fig. 8 *Efficiency of the monopole and notch in free space and on a standard hand/wrist phantom*

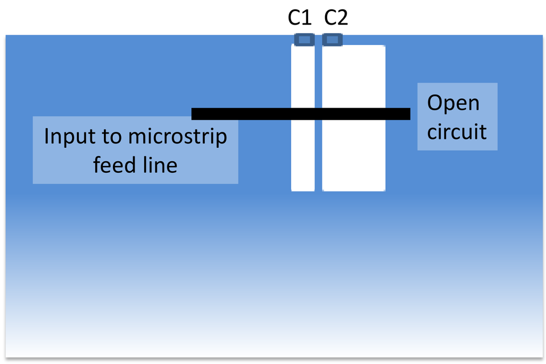


Fig. 9 *Two notches driven in series and having different resonant frequencies, tuned by C1 and C2. Here the feed line is terminated by a capacitive open circuit stub*

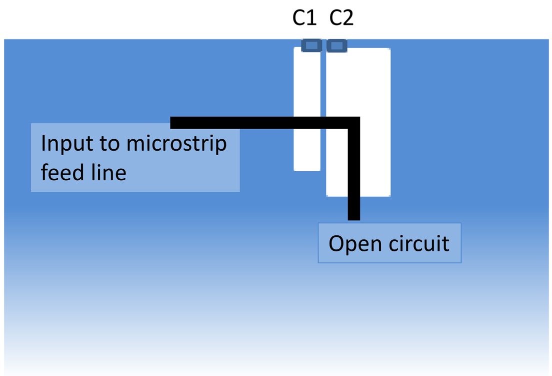


Fig. 10 *This example shows that by varying the feed geometry it is possible to choose the coupling of both loops independently*

As in the case of a single notch, the resonant frequency of each loop-notch is determined by its dimensions and the capacitance across its opening; the input resistance at resonance is determined by the degree of coupling provided by the geometry of the feed line. The arrangement shown in Fig. 10 suggests how the coupling from the feed to the two loops can be manipulated independently by adjusting the proportions of the notches as well as the position of the feed line. The notches are positioned in the long edge of the ground plane, whose lower edge is not shown in the figure. There is no specific relationship between the depth of the notches and the width of the ground plane. A selection of further configurations may be found in [19].

The simplicity of the arrangement and the low impedance of the feed system make it very easy to simulate the performance of these antennas with the usual EM design software and it will be found that there is great scope for variations on the basic designs shown here.

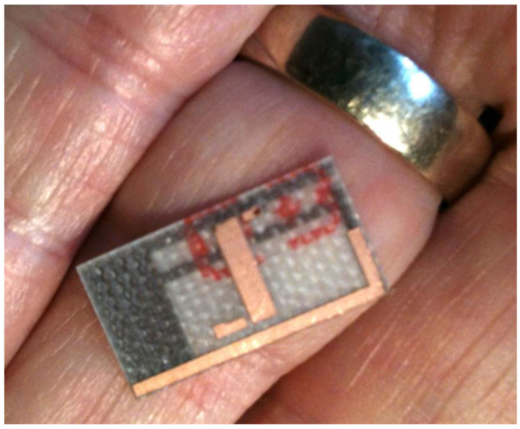


Fig. 11 *PCB for a 19 mm × 10 mm dual loop-notch covering the 850/900 and 1800/1900 MHz bands, suitable for incorporation into a 19 mm wide conductive strap*

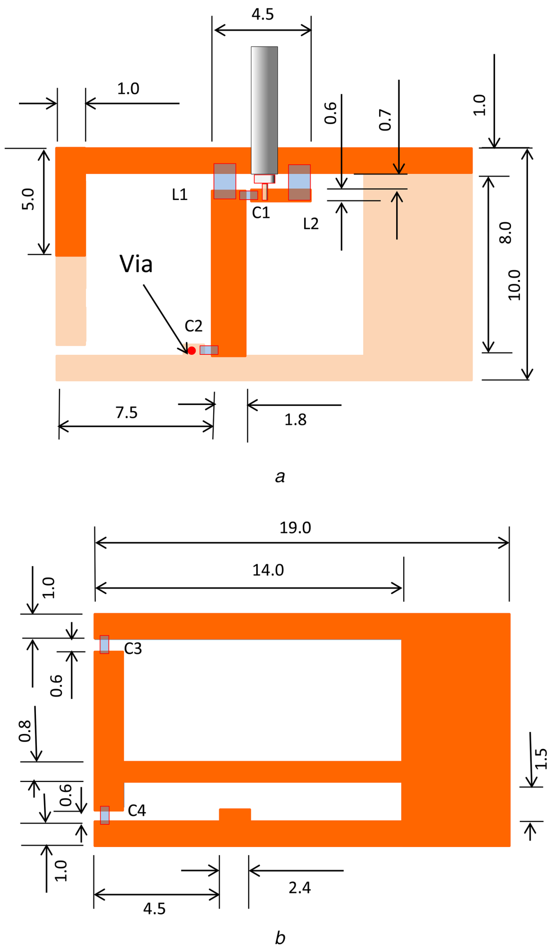


Fig. 12 *Dimensions of the watchstrap antenna shown in Fig. 11. C1 = 2p2, C2 = 0p7, C3 = 1p0. C4 = 0p6, L1 = 10 nH, L2 = 10 nH. The strap would extend up and down the page. For ease of understanding the lower copper layer is shown as if viewed through the PCB*

When incorporated into a strip conductor forming a wrist-strap it becomes more obvious that the loop-notch is a method for driving currents in the strip, effectively creating a form of the shunt-fed dipole. Figs. 11 and 12 show a dual-band antenna for incorporation in a watch strap. The two resonant notches are formed in the ground plane and are tuned using 0402 chip capacitors. The microstrip feed line crosses both notches and is terminated by C2; the antenna is fed by a 3-element matching circuit (C1, L1, L2) and all the chip components are contained within the antenna. When placed within a conductive strap the antenna provided the results as shown in Figs. 13 and 14.

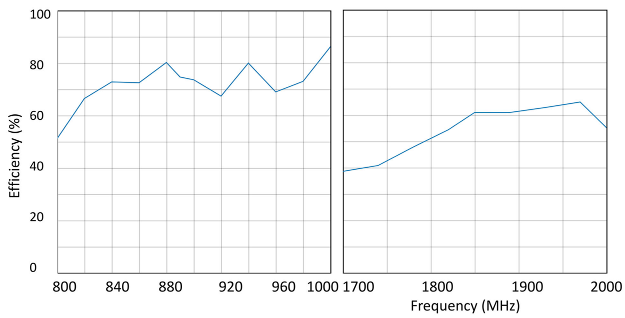


Fig. 13 *Efficiency of the notch of Fig. 12 in free space*

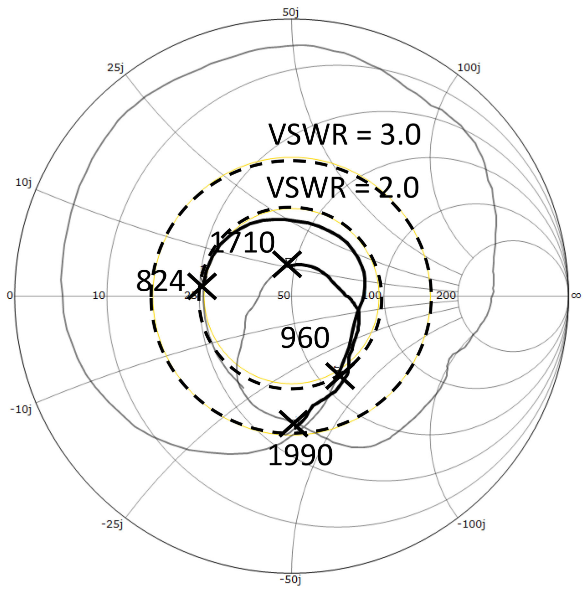


Fig. 14 *Impedance of the notch shown in Fig. 12. Frequency bands 824–960 and 1710–1950 MHz are highlighted*

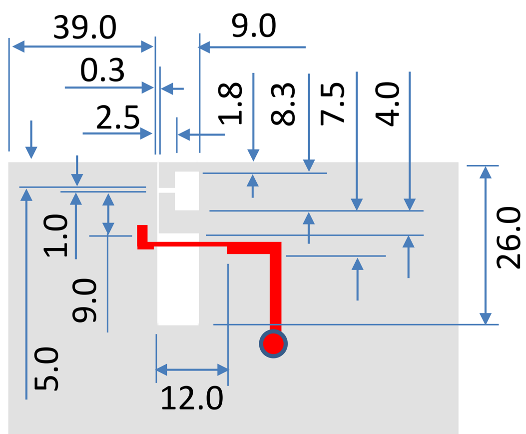


Fig. 15 *Compound 26 mm × 96 mm notch for 824–960 + 1710–2170 MHz. The feed track is 2.5 mm wide; the section across the notch is 1.3 mm wide. The 115 mm × 16 mm PCB is not shown to scale*

A further dual-band notch is shown in Fig. 15 where a 26 mm × 9 mm notch is formed in a 115 mm × 60 mm ground plane. In this example, the higher frequency resonance is provided by the structure within the larger aperture and tuning was achieved with no added capacitors.

The example shown in Fig. 7 was designed for use in a wrist-worn device with a ground plane 33 mm in diameter. To compare the performance of a loop-notch with a more conventional antenna one prototype device was fitted with a curved monopole antenna 25 mm in length (Fig. 7*a*), matched with a 0.9 pF chip capacitor in series with its feed. A second prototype was made using a 6 mm × 4 mm notch (Fig. 7*b*) fed by a microstrip line as shown. The notch was tuned by a 0.3 pF chip capacitor across its open edge. The 1.5 mm wide feed line was positioned 1 mm from the inner edge of the notch and extended 1.5 mm over the ground plane at its open circuit end.

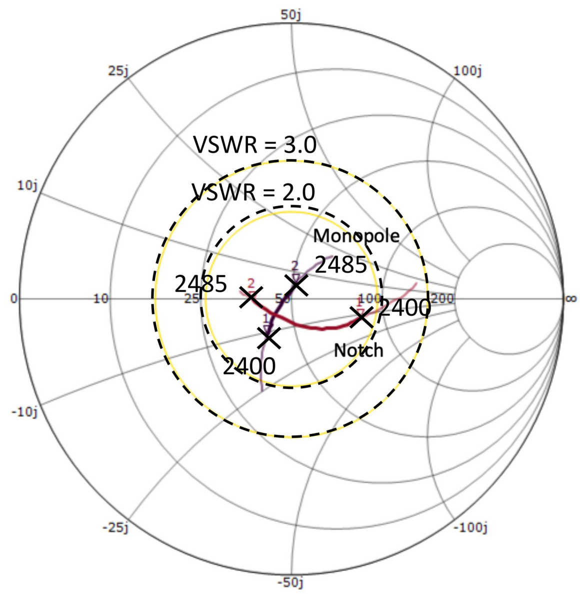


Fig. 16 *Input impedances of monopole and notch antennas*

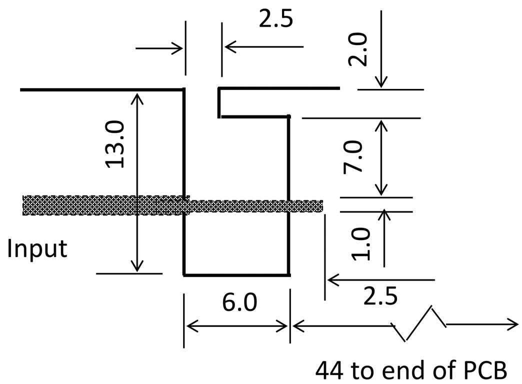


Fig. 17 *Details of 2.4/5 GHz notch formed on a 110 mm × 60 mm PCB*

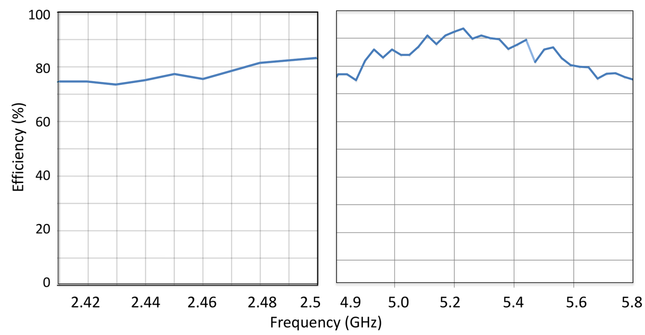


Fig. 18 *Efficiency of the loop-notch detailed in Fig. 17*

The input impedance of both antennas is shown in Fig. 16. Each PCB was fitted into a plastic case and its efficiency was measured both in free space and also on a SPEAG large male hand/wrist phantom. In free space the efficiencies of the two antennas were very similar, but as shown in Fig. 8, when placed on the phantom the efficiency of the PIFA fell by 5 dB relative to free space but that of the notch by only 3.5 dB. It is seen in Fig. 7 that the smaller area occupied by the notch releases significant surface area on both sides of the PCB that is available for circuit components.

A single notch providing dual-band operation is shown in Fig. 17, with its efficiency shown in Fig. 18. This notch is 13 mm × 6 mm, formed in a ground plane 110 mm × 60 mm, operating in the 2.4 and 5 GHz ISM bands. No additional tuning capacitance is required.

4 Discussion

It is clear that a ground plane and an embedded notch form a closely coupled resonant arrangement. As the notch is made smaller, to maintain the same tuned frequency, it must be increasingly loaded by the tuning capacitance, so its Q-factor increases.

There is no hard lower limit to the dimensions of the notch or those of the ground plane, but the rising Q-factor of the ground plane Q_2, limits efficiency and bandwidth performance in a classical manner as its dimensions diminish significantly below a half-wavelength.

The examples shown are in this paper are mostly simple arrangements with the notch in the ground plane on one side and the microstrip feed on the other side. In a practical case in which a PCB supports circuits on both outer faces, notch apertures are created on both outer faces of the PCB and in any internal copper layers, and vias are positioned to link the ground planes round the edges of the apertures as well as around the perimeter of the PCB, as seen in Fig. 7.

5 Observations

The forms of loop-notch antennas described above illustrate only some of the many possible configurations of this versatile format. A notable feature of these antennas is their high efficiency, which is usually very close to the maximum possible after allowing for the reflection loss caused by imperfect matching. Dielectric losses are low because the antennas are low impedance devices and only a small volume of the dielectric is subject to significant E-fields. Resistive losses are low because most of the current flows in the ground plane. The examples are self-matched, so no matching networks are needed. (The exception being the example of Fig. 11, where severe space constraints resulted in the use of chip components in the feed system). As discussed, the optimum position for a notch is along the edge of a ground plane, some distance from the end, but if some reduction in bandwidth is acceptable it can be placed near to a corner. A 2.4 GHz notch operates well enough for most Bluetooth™ applications even when placed at the corner of a very small ground plane.

Limited complete dimensions have been shown in this paper, but it will be found that optimisation of the simple structures shown in Figs. 3 and 17 can be accomplished very rapidly. Dual-band structures require more time-consuming optimisation, which can be accomplished either by simulation or experiment.

It is interesting to note the relationship between these loop-notch antennas and a variety of 'chip' antennas, most of which require to be mounted within an opening in the host ground plane and provided with a specified pattern of feed conductors, typically with overall dimensions similar to those of a loop-notch [20].

The dependence of effective radiation on currents flowing in the ground plane is very obvious for the loop-notch antenna. This dependence is not unique, but is an essential feature of any small antenna that is required to provide performance beyond the Chu-Harrington limit, whether a loop-notch, ceramic chip, PIFA or other format.

The small dimensions of the loop-notch can be set in context by comparing them with those of other design for small antennas in [5, 21, 22].

The design of circuits on both outer faces of the host PCB must take into account the flow of RF currents on both surfaces by avoiding breaks in the ground planes at right angles to the direction of current flow, and points at which the surface currents can couple into the inner layers of the PCB assembly [23]. These precautions should be taken whatever small antenna is used, so there are no new requirements for the loop-notch.

6 Conclusion

The hybrid loop-notch is an effective and flexible format for small antennas suitable for integration into a wide variety of wireless-connected devices. It has low cost, is simple to optimise, and can provide operation over wide or dual non-contiguous frequency bands.

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