

Three Centuries of UWB Antenna Development

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Abstract—This paper provides a historical overview of ultra-wideband (UWB) antennas. Early radio was narrowband in conception, but UWB in practice due to various technical limitations. Oliver Lodge pioneered UWB antenna engineering in the nineteenth century with his invention of both the biconical and bowtie antennas, and J.C. Bose demonstrated the first horn antennas in 1897. These nineteenth century spark-gap UWB antennas were largely forgotten until the 1930s and 1940s when advances in RF technology made short wavelength compact UWB antennas more practical. For lack of wide-scale implementation, many of these mid-century designs were forgotten in turn. By the closing decades of the twentieth century, UWB antennas were still considered “the main limiting factor of a UWB system.” A third century of development kicked off (more-or-less) with the FCC’s authorization of UWB wireless systems in 2002. A host of antenna designers re-discovered or re-invented twentieth century designs and advanced the UWB antenna arts further with innovations like compact planar implementations, UWB patch antennas, embedded UWB antennas, and spectral-filtered or frequency-notched designs. The three centuries of UWB antenna development have been characterized by the failure of successive generations of antenna designers to benefit from the lessons of earlier pioneers.

Keywords-antennas, ultra-wideband, history

I. INTRODUCTION

This paper aims to illustrate the frequency with which even the most talented antenna engineers waste time rediscovering concepts and designs well-known to earlier generations. This paper further seeks not only to acquaint the present generation of ultra-wideband (UWB) antenna designers with the works of their predecessors, but also to instill a healthy respect for the need to review and understand the history of antenna technology. The present work has evolved from a conference paper (now nine years old), through a magazine article, a book chapter, and various blog postings [1, 2, 3, 4].

This paper begins with a discussion of the nineteenth century radio pioneers who discovered radio waves, and created spark-gap radio. In the early twentieth century, radio came of age and more mature RF technology led the UWB expedients of the nineteenth century to be forgotten. A new generation of engineers pioneered antennas for HF through microwave applications, largely in ignorance of nineteenth century work. These antennas included horn and reflector antennas, frequency independent antennas and a variety of other designs. For lack of wide spread application, many of these twentieth century designs were forgotten in turn. As the

twenty-first century dawned, renewed interest in UWB technology led to renewed attention UWB antennas. This paper surveys the three centuries of UWB antenna development.

II. NINETEENTH CENTURY UWB ANTENNAS

A. Heinrich Hertz and Radio Waves

Heinrich Hertz was not the first to experiment with radio waves. Contemporaries such as Charles Hughes and Oliver Lodge performed similar work in parallel. What set Hertz apart, however, was his tenacity in teasing out the properties of electromagnetic waves from the brilliant use of crude instrumentation [5]. Hertz further provided a comprehensive theoretical framework for understanding radio waves. Among Hertz’s antenna discoveries were the half-wave dipole, end-loaded dipole, and the parabolic reflector of Fig. 1 [6].

B. Jagadis Chandra Bose and Millimeter Waves

In 1897, Indian physicist Jagadis Chandra Bose demonstrated a complete system for transmitting and receiving radio waves at millimeter-wave frequencies of around 60GHz. This system included what Bose dubbed “collecting funnels,” the first horn antennas. Bose used a spark-gap transmitter and a semiconductor junction as a receiver. Fig. 1 reproduces one of Bose’s figures showing a pyramidal horn, and shows a sketch of one of Bose’s conical horn antennas. Darrel Emerson provides an excellent and detailed description of Bose’s pioneering work [7].

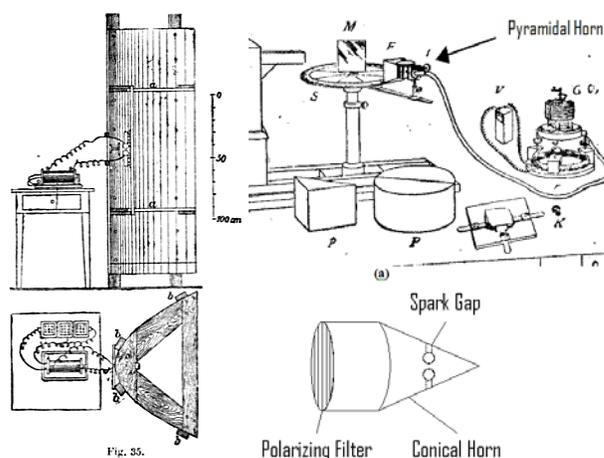


Fig. 1. Hertz’s parabolic reflector (left), Bose’s pyramidal horn (top right), and Bose’s conical horn (bottom right) (after [6] and [7]).

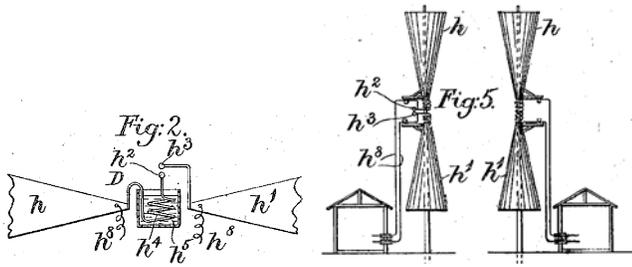


Fig. 2. Oliver Lodge invented the bowtie antenna (left) and the biconical antenna (right) [8].

C. Oliver Lodge and the Invention of Radio

In 1898, Sir Oliver Lodge (1851-1940) patented the first syntonic or tuned radio system. Ironically, the very patent that inaugurated this fundamental concept of narrow-band, frequency-domain radio also disclosed some of the first UWB antennas:

As charged surfaces or capacity areas, spheres or square plates or any other metal surfaces may be employed; but I prefer, for the purpose of combining low resistance with great electrostatic capacity, cones or triangles or other such diverging surfaces with the vertices adjoining and their larger areas spreading out into space; or a single insulated surface may be used in conjunction with the earth, the earth or conductors embedded in the earth constituting the other oppositely-charged surface [8].

Lodge further invented the concept of a monopole or monocone. Fig. 2 shows Lodge’s 1898 bowtie and biconical antennas. Marconi eventually acquired Lodge’s patents.

D. Guglielmo Marconi and the Radio Business

Marconi was among the first to realize the possibility of radio communication. Others (including Lodge) had demonstrated the feasibility of signaling via radio waves but were slow to grasp the commercial implications. Marconi was convinced that this scientific curiosity had practical applications, saying: “If we had attributed to the power of light only the possibilities offered by a candle, we would never have built lighthouses and reflectors” [9]. Marconi’s original antennas were little changed from those used by Hertz, including parabolic reflectors and square plate antennas [10]. As Marconi moved to high-power, longer-range systems, he adopted fan and conical monopole antennas [11, 12].

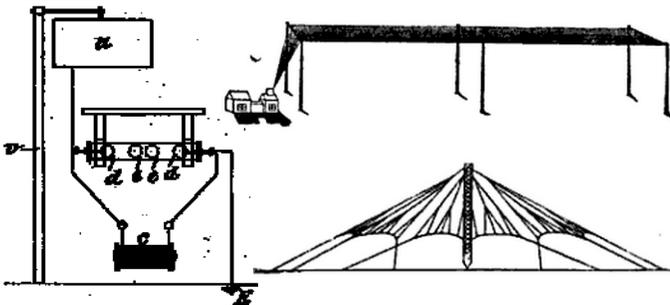


Fig. 3. Marconi’s original square plate antenna (left) [10]. Marconi’s bent or directive antenna (top right) and “umbrella” antenna (bottom right) [11].

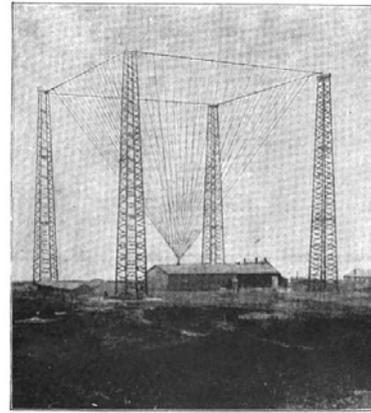


Fig. 4. Square monocone antenna at Cape Breton, Nova Scotia [12].

E. Spark Gap and UWB

Some commentators depict the history of RF technology as having come full circle from the early days of UWB-like spark gap signals through narrowband RF technology and back to spread spectrum and UWB concepts. This fiction makes an engaging story, but does injustice to the ingenuity of radio’s pioneers. To the contrary, early radio was narrowband in conception. As early as 1892, vacuum tube pioneer and radio visionary William Crookes described how a radio system would comprise multiple channels, each operating on a particular frequency or wavelength [13]. The damped sinusoid waveforms and spark gap transmissions of the first radio systems may have been UWB in practice, but that was only because then existing radio technology did not allow the early radio pioneers to create narrow band implementations.

III. TWENTIETH CENTURY UWB ANTENNAS

Radio grew slowly into the narrowband conception of the spark-gap pioneers. With improved transmitter and receiver technology, spark-gap radio was left behind, and eventually outlawed in 1912. UWB antenna designs were no longer necessary to squeeze the maximum performance from an RF system. As more narrowband designs came into wide use, the original UWB antenna designs were largely forgotten.

The frontiers of radio science surged past 30MHz in the 1930s, and a new generation of antenna designers tackled the problem of creating broadband antennas. As frequencies used in RF systems increased and wavelengths became shorter, interest in high-performance, broadband antennas grew. Shorter wavelengths made complicated quarter-wavelength-scale antenna elements more practical. Not only were frequencies higher but also bandwidths were wider. More sophisticated signals placed greater demands on antennas than the traditional 10kHz wide amplitude modulation (AM) of commercial broadcast radio systems. Edwin Howard Armstrong’s 1933 invention of wideband frequency modulation (FM) signals demanded bandwidths of 150kHz or more. The advent of television also led to a demand for antennas that could handle the much wider bandwidths associated with video signals, typically about 6MHz wide.

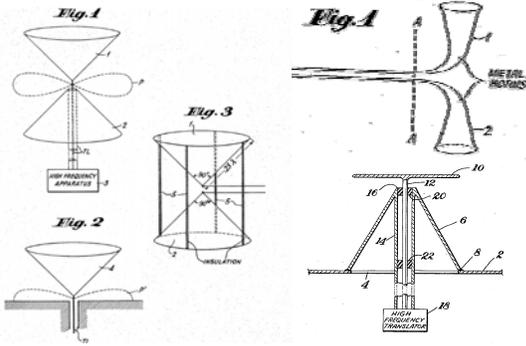


Fig. 5. Biconical and monocone antennas “invented” by Carter (left and center) [15], Carter’s tapered feed line concept (top right) [16], and Kandoian’s discone (bottom right) [17, 18].

A. Rediscovery of the Biconical Antenna

This renewed demand for wideband antennas led Harold Wheeler to rediscover and “invent” the biconical antenna. In preparing a patent application, Wheeler’s attorney discovered Lodge’s publication and Wheeler abandoned the application [14]. Two or three years later, Wheeler’s friend, RCA engineer Phillip Carter similarly rediscovered the biconical antenna and conical monopole. His patent attorney and the patent examiners were unfamiliar with Lodge’s work, and Carter was awarded a patent for the biconical antenna in 1939 [15]. In another invention, Carter also improved upon Lodge’s original design by incorporating a tapered feed [16]. Carter was among the first to take the key step of incorporating a broadband transition between a feed line and radiating elements. Armig Kandoian improved upon the biconical with his discone antenna [17, 18]. Fig. 5 shows these antennas.

B. Bulbous UWB Elements

The fundamental principle that “fatter” or “thicker” antennas have enhanced bandwidth began to be understood in the late 1930s and early 1940s [19, 20]. Sergei Schelkunoff pioneered the analysis of the biconical antenna and proposed a spherical dipole [21]. With Harald Friis, Schelkunoff studied a tapered biconical with uniform capacitance per unit length [22, 23]. Perhaps the premier design of this kind was Nils Lindenblad’s tapered monopole – a beauty of both art-deco design and the RF arts [24, 25]. Lindenblad’s antenna graced both the top of the Empire State Building and the cover of Forbes magazine, January 15, 1945 [26]. Lindenblad’s work also inspired John Kraus’ “Volcano Smoke” antenna [27, 28]. Fig. 6 shows these antennas.

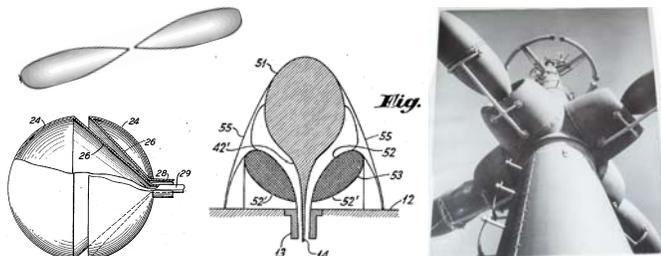


Fig. 6. Schelkunoff-Friis isocapacitive tapered dipole (top left) [19], Schelkunoff’s spherical dipole (bottom left) [21], Lindenblad’s element in cross-section (center) [24], and the Empire State deployment (right) [26].

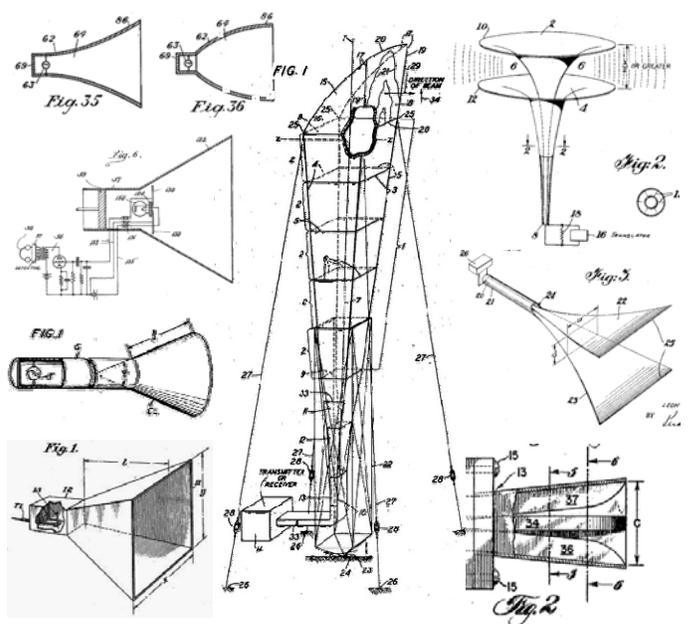


Fig. 7. Southworth’s dielectric horn (top-most left) [29], Barrow’s electromagnetic horn (top left) [30], King’s conical horn (bottom left) [30], Katzin’s pyramidal horn (bottom-most left) [31], Beck’s and Friis’s horn-reflector (center) [32], Brillouin’s tapered horns (right top and center) [35], and Jones et al’s quad ridged horn (bottom right) [38].

C. Rediscovery of the Horn Antenna

George Southworth pioneered dielectric horns as early as the 1930s [29] and Wilmer Barrow devised a square horn in 1938 [30]. During the war, King rediscovered Bose’s conical horn antenna [31], and Katzin rediscovered Bose’s pyramidal horn antenna [32]. Perhaps the most successful horn design of the era was the horn-reflector antenna pioneered by A.C. Beck and Harald Friis [33, 34]. Their horn-reflector antenna was the foundation of ATT’s nationwide long distance telephone microwave network. Although largely mothballed today, these antennas remain a familiar sight. Leon Brillouin invented imaginative horn antennas that tapered continuously from coaxial feed lines to their apertures [35]. S. B. Cohn’s 1947 analysis of ridge waveguides led the foundation for the development of the ridged horn [36, 37]. Ernest Jones, James D. Leonard, and Daniel F. Yaw devised a circularly polarized ridged horn in the late 1950s [38]. Fig. 7 shows these horns.

D. Toward More Manufacturable Designs

3-D or volumetric shapes with precise mathematical tapers deliver outstanding performance at the cost of difficult and expensive manufacturing. One solution is to capture most of the benefit of the precise taper by using a more readily available shape. For instance, Walter Stöhr discovered that relatively simple spherical elements work well [39].

For commercial and high volume applications, however, planar designs offer substantial cost advantages. Phillip Carter continued to follow in Lodge’s footsteps with a thin wire version of the bow tie antenna [40], and ten years later with Henry A. White’s bowtie array TV antenna [41] as well as the work of George Brown and O.M. Woodward [42].

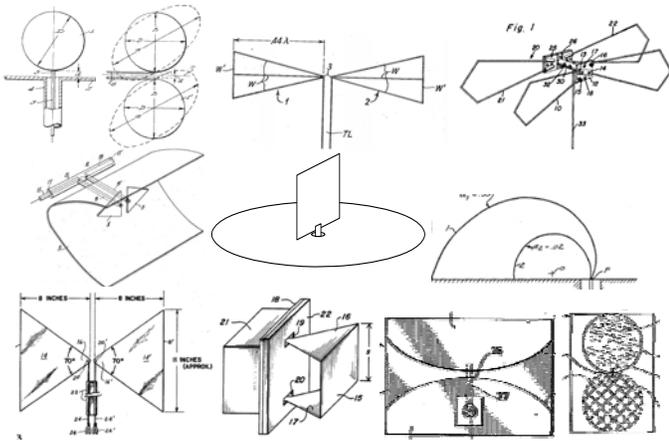


Fig. 8. Stöhr's spherical and ellipsoidal monopoles and dipoles (top left) [39], Carter's thin wire bowtie (top center) [40], White's thin wire bowtie array (top right) [41], Master's diamond dipole (middle left) [43], Lamberty's square monopole (middle center) [44], Turner's scimitar antenna (middle left) [45], Velez's bowtie antenna (bottom far left) [46], Harmuth's current sheet (bottom left) [47], Lalezari et al's notch (bottom right) [48], and Thomas et al's circle dipole (bottom far right) [49].

Similarly in the 1940s, Robert W. Masters proposed an inverted triangular or "diamond" dipole for use with an ultrahigh frequency (UHF) television receiver [43]. B. J. Lamberty revived Marconi's square plate elements to create a simple-to-build, compact, inexpensive UWB monopole element in 1957 [44]. Edwin and William Turner devised the 1:10 bandwidth scimitar antenna for use in missile and airborne applications [45]. Joseph Valez invented a bowtie antenna for UHF reception in the late 1960s [46]. In the 1980's Henning Harmuth pioneered the current sheet antenna [47], while Farzin Lalezari, Charles Gilbert, and John Rogers introduced the notch, or half-circle, planar antenna [48]. Mike Thomas and Ronald Wolfson proposed a planar circular dipole element in a 1994 patent [49]. Fig. 8 shows all these more manufacturable antennas.

The planar approach also entered horn antenna design. Coleman J. Miller employed a planar ridge element inside a horn antenna as early as 1951 [50]. By the 1980's similar planar antenna elements began to emerge from Nester and others [51]. Fig. 9 shows these planar horn antennas.

E. Slot Antennas

Slot antennas were devised as early as 1938 by Alan Blumlein [52], and came of age in the 1940's [53-55]. Schelkunoff and Friis presented a variety of tapered slot feeds in their 1952 text [56], and George Robert-Pierre Marié received a patent for a wide-band tapered slot in 1965 [57]. Fig. 9 also shows these slot antennas.

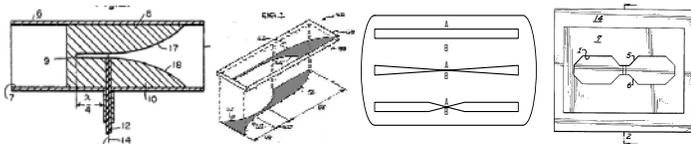


Fig. 9. Miller's planar ridge horn (far left) [50], Nester's planar horn (left) [51], tapered slots from Schelkunoff and Friis (right) [56], and Marié's tapered slot (far right) [57].

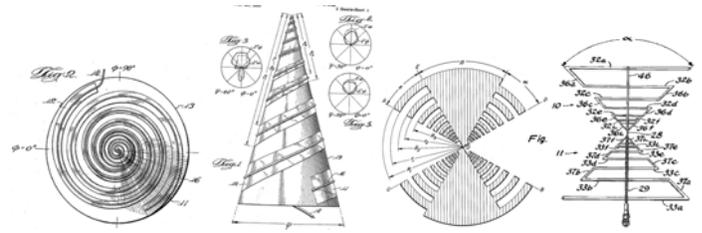


Fig. 10. Dyson's planar spiral (far left) [58], Isbell's and Du Hamel's frequency-independent antenna (right) [59, 60] and Du Hamel's log periodic antenna (far right) [61].

F. Frequency Independent Antennas

John D. Dyson invented the first practical frequency-independent antenna: the planar and conical spirals, while a student at the University of Illinois in the late 1950's [58]. Raymond Du Hamel and Dwight E. Isbell invented a frequency independent antenna [59, 60], and Du Hamel devised the log periodic antenna soon thereafter [61]. Victor Rumsey identified the principle at the heart of a large family of broadband antennas [62]. The impedance and pattern properties of an antenna will be frequency-independent if the antenna shape is specified only in terms of angles. These frequency-independent antennas have bandwidth limited only by the range over which a repetitive geometry is scaled. In each of these frequency-independent antennas, a small-scale portion radiates high frequencies, and a large-scale portion radiates low frequencies. The effective origin, or phase center, of the antenna moves with frequency. These antennas are prone to dispersion and not suitable for all UWB applications [63]. Fig. 10 shows these frequency-independent antennas.

IV. TWENTY-FIRST CENTURY UWB ANTENNAS

By closing decades of the twentieth century, advances in RF technology once again spurred interest in UWB antennas. In 1984, UWB pioneer Henning Harmuth observed [64]:

"Over the last few years, much has been published about the principles and applications of electromagnetic waves with large relative bandwidth, or non-sinusoidal waves for short. The next step is the development of the technology for the implementation of these applications. It is generally agreed that the antennas pose the most difficult problem....."

Despite more than a century of UWB progress, the dawn of UWB's third century rose on a variety of skeptics convinced that UWB antenna technology was inadequate for the demands of UWB systems. One government report argued in early 2000 [65]:

"The main limiting factor of a UWB system is the antenna, which acts as a filter and limits the transmission bandwidth.... The problems associated with building high fractional bandwidth antennas are likely to restrict the bandwidth of low frequency range UWB systems."

Once again, the wealth of available UWB antenna designs and concepts had been partly forgotten, only to be rediscovered by the current generation of antenna designers.

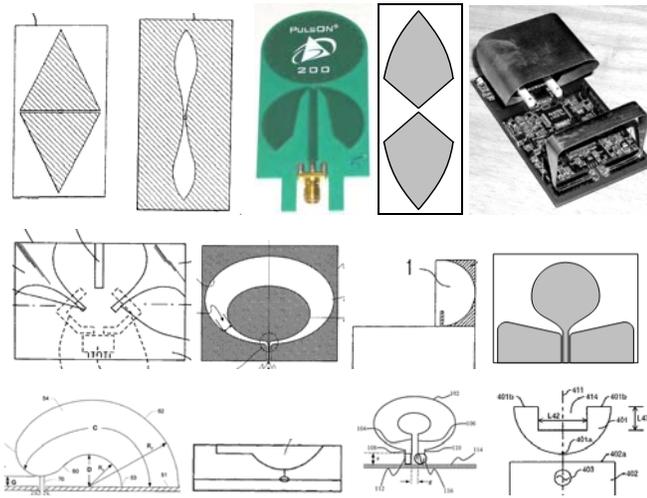


Fig. 11. Fullerton's "diamond dipole" (top far left) [66], Barnes' COTAB UWB slot (top left) [68], the author's planar dipole (top right) [74], Starkie's Bishop's Hat antenna (top right) [after 76], AetherWire locator (top far right) [77], Aiello's dual horn (middle left) [78], McCorkle's magnetic slot antenna (middle center) [79], Hasegawa's semi-circular monopole chip antenna (middle right) [80], Zollinger's planar monopole (middle far right) [84], the author's monoloop (bottom, far left) [85], Chen's terminated monopole slot (bottom left) [86], one of Chen's embedded monopoles [86], Chen's terminated monopole slot (bottom, right), and Okado's monopole (bottom far right) [87].

A. Planar Antennas

The manufacturability of planar antennas continued to draw attention. Larry Fullerton resurrected Robert Master's diamond dipole [66, 67] and Mark Barnes optimized the Marié slot for use in a through-wall radar [68, 69] at the Time Domain Corporation. The author re-discovered Thomas' and Wolfson's circle dipoles, optimized them using elliptical form factors [70], and pioneered one of the earliest commercial UWB antenna designs – a microstrip-fed planar dipole also reminiscent of the Lindenblad element, also for Time Domain [71-74].

Other commercial designs included Timothy Starkie's and Les Smith's "Bishop's Hat" antenna for Artimi (which became Veebeam) [75-76], a dual horn design by Robert Aiello and Patricia Foster for Fantasma Networks (later Stacatto, which became part of Veebeam) [78], John McCorkle's magnetic slot antenna for XtremeSpectrum (later acquired by Motorola and then spun out in Freescale) [79], and a semi-circular monopole by Minoru Hasegawa, Takao Shimamori, Yong-Jin Kim, and Do-Hoon Kwon for Samsung [80-81]. Fig. 11 shows all these designs.

Honda introduced disk or circular monopoles in 1992 [81] and Agarwal adapted them with elliptical elements a few years later [82]. Ernst Zollinger devised a tapered co-planar-waveguide-fed planar monopole element reminiscent of a cross-section of the 1930s vintage Lindenblad element [84]. The author rediscovered and updated Turner's "scimitar" antenna to yield a "monoloop" antenna [85]. Other recent monopole innovations include Chen's embedded and terminated slot monopoles [86, 87], and Okado's monopole [88]. Fig. 11 also shows these monopole designs.

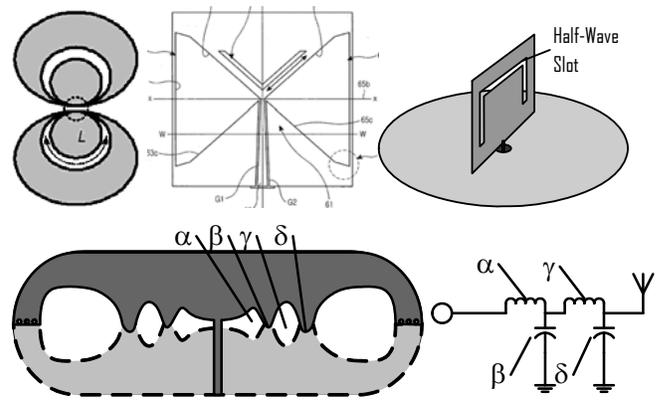


Fig. 12. One of the author's resonant structure frequency notched UWB antenna designs [after 90, 91] (upper left), Kim's frequency-notched bowtie slot (upper center) [92], and Kerkhoff's notched monopole (upper right) [93]. Stepped impedance line filtering technique varies antenna impedance (bottom left) to yield other spectral responses (bottom right) [94].

B. Spectral Control and Frequency Notching

One recent advance in UWB antennas is the development of techniques to adjust and control the spectral response of UWB antennas. Aaron Kerkhoff and Hao Ling reported on applying genetic algorithm (GA) optimization techniques for spectral notching as early as 2003 [89]. Also in 2003, the author (along with Wolynec and Myszkka) disclosed incorporating resonant structures to yield spectral notches [90], the basis of a family of frequency notched antenna designs [91]. Yong Jin Kim, Do-Hoon Kwon and Seong-Soo Lee devised a frequency-notched bowtie slot [92, 93], and Kerkhoff and Ling updated Lamberty's square monopole element with a resonant half wavelength slot [94]. Antennas are inherently high pass filters. Using stepped-impedance filter techniques, one may insert a low pass response into an antenna. Although the series inductor and shunt capacitor behavior of stepped impedance filters is ideal for low pass filter responses, these techniques may be applied to other filters as well [95]. Fig. 12 shows these spectral antennas.

C. Other Recent Advances

Fractal antennas have shown some promise [96], although others are skeptical [97]. Another recent advance is the development of wideband patch antennas such as the multi-level patch antenna of Carles Puente Baliarda, Carmen Borja Borau, Jaume Anguera Pros, and Jordi Soler Castany for Fractus [98].

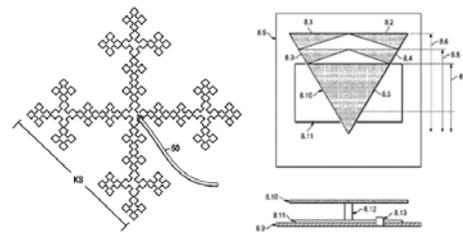


Fig. 13. Cohen's fractal antenna (left) [95], and Puentes' multi-level broadband patch antenna.

V. CONCLUSION

The three centuries of UWB antenna development have been characterized by the failure of successive generations of antenna designers to benefit from the lessons of earlier pioneers. A familiarity with the history of the antenna art is essential for any serious antenna designer who aims to implement novel designs rather than recreate the antennas of previous generations.

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