CHAPTER ONE

A MICROHISTORY OF MICROWAVE TECHNOLOGY

1.1 INTRODUCTION

Many histories of microwave technology begin with James Clerk Maxwell and his equations, and for excellent reasons. In 1873, Maxwell published *A Treatise on Electricity and Magnetism,* the culmination of his decade-long effort to unify the two phenomena. By arbitrarily adding an extra term (the "displacement current") to the set of equations that described all previously known electromagnetic behavior, he went beyond the known and predicted the existence of electromagnetic waves that travel at the speed of light. In turn, this prediction inevitably led to the insight that light itself must be an electromagnetic phenomenon. Electrical engineering students, perhaps benumbed by divergence, gradient, and curl, often fail to appreciate just how revolutionary this insight was.[1] Maxwell did not introduce the displacement current to resolve any outstanding conundrums. In particular, he was not motivated by a need to fix a conspicuously incomplete continuity equation for current (contrary to the standard story presented in many textbooks). Instead he was apparently inspired more by an aesthetic sense that nature simply should provide for the existence of electromagnetic waves. In any event the word *genius,* though much overused today, certainly applies to Maxwell, particularly given that it shares origins with *genie*. What he accomplished was magical and arguably ranks as the most important intellectual achievement of the 19th century.[2]

Maxwell – genius and genie – died in 1879, much too young at age 48. That year, Hermann von Helmholtz sponsored a prize for the first experimental confirmation of Maxwell's predictions. In a remarkable series of investigations carried out between

[1] Things could be worse. In his treatise of 1873, Maxwell expressed his equations in terms of *quaternions.* Oliver Heaviside and Josiah Willard Gibbs would later reject quaternions in favor of the language of vector calculus to frame Maxwell's equations in the form familiar to most modern engineers.

[2] The late Nobel physicist Richard Feynman often said that future historians would still marvel at Maxwell's work, long after another event of that time – the American Civil War – had faded into merely parochial significance.

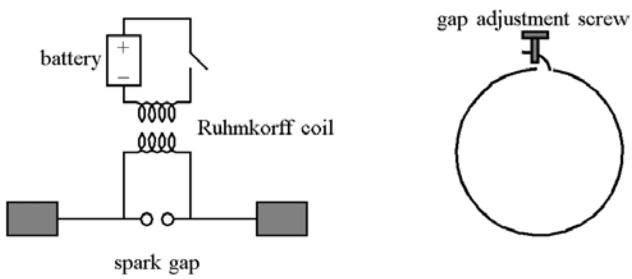

FIGURE 1.1. Spark transmitter and receiver of Hertz

1886 and 1888 at the Technische Hochschule in Karlsruhe, Helmholtz's former pupil, Heinrich Hertz, verified that Maxwell was indeed correct. Another contestant in the race, Oliver Lodge (then a physics professor at University College in Liverpool), published his own confirmation one month after Hertz, having interrupted his work in order to take a vacation. Perhaps but for that vacation we would today be referring to *lodgian waves* with frequencies measured in *megalodges.* Given that *Hertz* is German for *heart* and that the human heart beats about once per second, it is perhaps all for the best that Lodge didn't win the race.

How did Hertz manage to generate and detect electromagnetic waves with equipment available in the 1880s? Experimental challenges certainly extend well beyond the mere generation of some sort of signal; a detector is required, too. Plus, to verify wave behavior, you need apparatus that is preferably at least a couple of wavelengths in extent. In turn, that requirement implies another: sufficient lab space to contain apparatus of that size (and preferably sufficient to treat the room as infinitely large, relative to a wavelength, so that unwanted reflections from walls and other surfaces may be neglected). Hertz, then a junior faculty member, merited a modest laboratory whose useful internal dimensions were approximately 12 m by 8 m.[3] Hertz understood that the experimental requirements forced him to seek the generation of signals with wavelengths of the order of a meter. He accomplished the difficult feat of generating such short waves by elaborating on a speculation by the Irish physicist George Francis FitzGerald, who had suggested in 1883 that one might use the known oscillatory spark discharge of Leyden jars (capacitors) to generate electromagnetic waves. Recognizing that the semishielded structure of the jars would prevent efficient radiation, Hertz first modified FitzGerald's idea by "unrolling" the cylindrical conductors in the jars into flat plates. Then he added inductance in the form of straight wire connections to those plates in order to produce the desired resonant frequency of a few hundred megahertz. In the process, he thereby invented the dipole antenna. Finally, he solved the detection problem by using a ring antenna with an integral spark gap. His basic transmitter–receiver setup is shown in Figure 1.1. When the

[3] Hugh G. J. Aitken, *Syntony and Spark,* Princeton University Press, Princeton, NJ, 1985.

switch is closed, the battery charges up the primary of the Ruhmkorff coil (an early transformer). When the switch opens, the rapid collapse of the magnetic field induces a high voltage in the secondary, causing a spark discharge. The sudden change in current accompanying the discharge excites the antenna to produce radiation.

Detection relies on the induction of sufficient voltage in the ring resonator to produce a visible spark. A micrometer screw allows fine adjustment, and observation in the dark permits one to increase measurement sensitivity.[4]

With this apparatus (a very longwave version of an optical interferometer), Hertz demonstrated essential wave phenomena such as polarization and reflection.[5] Measurements of wavelength, coupled with analytical calculations of inductance and capacitance, confirmed a propagation velocity sufficiently close to the speed of light that little doubt remained that Maxwell had been right.[6]

We will never know if Hertz would have gone beyond investigations of the pure physics of the phenomena to consider practical uses for wireless technology, for he died of blood poisoning (from an infected tooth) in 1894 at the age of 36. *Brush and floss after every meal, and visit your dentist regularly.*

Maxwell's equations describe electric and magnetic fields engaged in an eternal cycle of creation, destruction, and rebirth. Fittingly, Maxwell's death had inspired von Helmholtz to sponsor the prize which had inspired Hertz. Hertz's death led to the publication of a memorial tribute that, in turn, inspired a young man named Guglielmo Marconi to dedicate himself to developing commercial applications of wireless. Marconi was the neighbor and sometime student of Augusto Righi, the University of Bologna professor who had written that tribute to Hertz. Marconi had been born into a family of considerable means, so he had the time and finances to pursue his dream.[7] By early 1895, he had acquired enough apparatus to begin experiments in and around his family's villa, and he worked diligently to increase transmission distances. Marconi used Hertz's transmitter but, frustrated by the inherent limitations of a spark-gap detector, eventually adopted (then adapted) a peculiar creation that had been developed by Edouard Branly in 1890. As seen in Figure 1.2, the device, dubbed a *coherer* by Lodge, consists of a glass enclosure filled with a loosely packed and perhaps slightly oxidized metallic powder. Branly had accidentally discovered that the resistance of this structure changes dramatically when nearby

[4] Hertz is also the discoverer of the photoelectric effect. He noticed that sparks would occur more readily in the presence of ultraviolet light. Einstein would win his Nobel prize for providing the explanation (and not for his theory of relativity, as is frequently assumed).

[5] The relative ease with which the waves were reflected would inspire various researchers to propose crude precursors to radar within a relatively short time.

[6] This is not to say that everyone was immediately convinced; they weren't. Revolutions take time.

[7] Marconi's father was a successful businessman, and his mother was an heiress to the Jameson Irish whiskey fortune. Those family connections would later prove invaluable in gaining access to key members of the British government after Italian officials showed insufficient interest. The British Post Office endorsed Marconi's technology and supported its subsequent development.

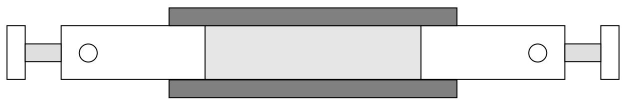

FIGURE 1.2. Branly's coherer

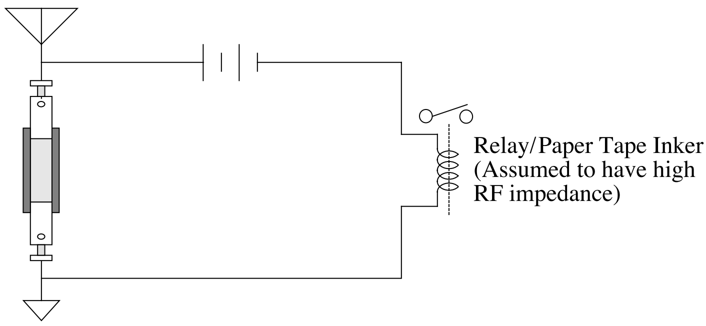

FIGURE 1.3. Typical receiver with coherer

electrical apparatus is in operation. It must be emphasized that the detailed principles that underlie the operation of coherers remain mysterious, but that ignorance doesn't prevent us from describing their electrical behavior.[8]

A coherer's resistance generally has a large value (say, megohms) in its quiescent state and then drops to kilohms or less when triggered by some sort of an EM event. This large resistance change in turn may be used to trigger a solenoid to produce an audible click, as well as to ink a paper tape for a permanent record of the received signal. To prepare the coherer for the next EM pulse, it has to be shaken (or stirred) to restore the "incoherent" high-resistance state. Figure 1.3 shows how a coherer can be used in a receiver. It is evident that the coherer is a digital device and therefore unsuitable for uses other than radiotelegraphy.

The coherer never developed into a good detector, it just got less bad over time. Marconi finally settled on the configuration shown in Figure 1.4. He greatly reduced the spacing between the end plugs, filled the intervening space with a particular mixture of nickel and silver filings of carefully selected size, and partially evacuated the tube prior to sealing the assembly. As an additional refinement in the receiver, a solenoid provided an audible indication in the process of automatically whacking the detector back into its initial state after each received pulse.

Even though many EM events other than the desired signal could trigger a coherer, Marconi used this erratic device with sufficient success to enable increases

[8] Lodge named these devices *coherers* because the filings could be seen to stick together under some circumstances. However, the devices continue to function as detectors even without observable physical movement of the filings. It is probable that oxide breakdown is at least part of the explanation, but experimental proof is absent for lack of interest in these devices.

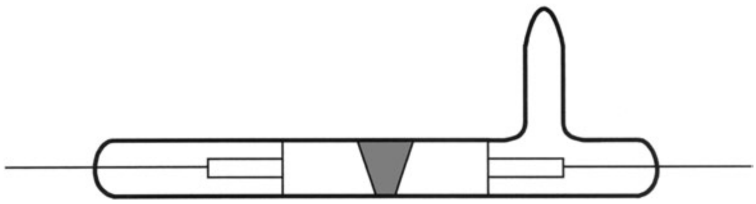

FIGURE 1.4. Marconi's coherer

in communication range to about three kilometers by 1896. As he scaled upward in power, he used progressively larger antennas, which had the unintended side effect of lowering the "carrier" frequencies to below 100 kHz from his initial frequencies of ~100 MHz. This change was most fortuitous, because it allowed reflections from the ionosphere (whose existence was then unknown) to extend transmission distances well beyond the horizon, allowing him to claim successful transatlantic wireless communications by 12 December 1901.[9] Wireless technology consequently ignored the spectrum above 1 MHz for nearly two more decades, thanks to a belief that communication distances were greatest below 100 kHz.

As the radio art developed, the coherer's limitations became increasingly intolerable, spurring the search for improved detectors. Without a body of theory to impose structure, however, this search was haphazard and sometimes took bizarre turns. A human brain from a fresh cadaver was once tried as a coherer, with the experimenter claiming remarkable sensitivity for his apparatus.[10]

That example notwithstanding, most detector research was based on the vague notion that a coherer's operation depends on some mysterious property of imperfect contacts. Following this intuition, a variety of experimenters stumbled, virtually simultaneously, on various types of point-contact crystal detectors. The first patent application for such a device was filed in 1901 by the remarkable Jagadish Chandra Bose for a detector using galena (lead sulfide).[11] See Figures 1.5 and 1.6. This detector exploits a semiconductor's high temperature coefficient of resistance, rather than rectification.[12] As can be seen in the patent drawing, electromagnetic

[9] Marconi's claim was controversial then, and it remains so. The experiment itself was not double-blind, as both the sender and the recipient knew ahead of time that the transmission was to consist of the letter *s* (three dots in Morse code). Ever-present atmospheric noise is particularly prominent in the longwave bands he was using at the time. The best modern calculations reveal that the three dots he received had to have been noise, not signal. One need not postulate fraud, however. Unconscious experimenter bias is a well-documented phenomenon and is certainly a possibility here. In any case, Marconi's apparatus evolved enough within another year to enable verifiable transatlantic communication.

[10] A. F. Collins, *Electrical World and Engineer,* v. 39, 1902; he started out with brains of other species and worked his way up to humans.

[11] U.S. Patent #755,840, granted 19 March 1904. The patent renders his name Jagadis Chunder Bose. The transliteration we offer is that used by the academic institution in Calcutta that bears his name.

[12] Many accounts of Bose's work confuse his galena balometer with the point-contact rectifying ("catwhisker" type) detectors developed later by others and thus erroneously credit him with the

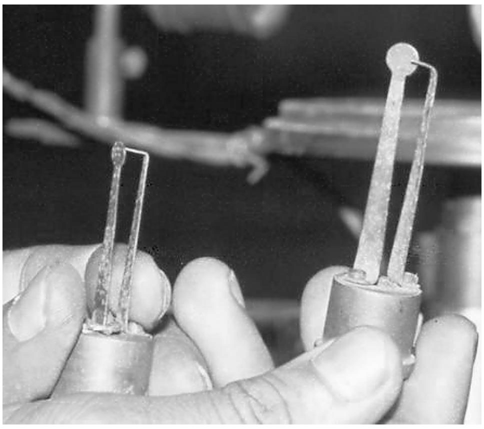

FIGURE 1.5. Actual detector mounts used by Bose (galena not shown) [*courtesy of David Emerson*]

radiation is focused on the point contact, and the resistance change that accompanies the consequent heating registers as a change in current flowing through an external circuit. This type of detector is known as a *bolometer.* In refined form, bolometers remain useful as a means of measuring power, particularly of signals whose frequency is so high that there are no other means of detection. Bose used this detector in experiments extending to approximately 60 GHz, about which he first published papers in 1897.[13] His research into millimeter-wave phenomena was decades ahead of his time.[14] So too was the recognition by Bose's former teacher at Cambridge, Lord Rayleigh, that hollow conductors could convey electromagnetic energy.[15] Waveguide transmission would be forgotten for four decades, but Rayleigh had most of it worked out (including the concept of a cutoff frequency) in 1897.

invention of the semiconductor diode. The latter functions by rectification, of course, and thus does not require an external bias. It was Ferdinand Braun who first reported asymmetrical conduction in galena and copper pyrites (among others), back in 1874, in "Ueber die Stromleitung durch Schwefelmetalle" [On Current Flow through Metallic Sulfides], *Poggendorff's Annalen der Physik und Chemie,* v. 153, pp. 556–63. Braun's other important development for wireless was the use of a spark gap in series with the primary of a transformer whose secondary connects to the antenna. He later shared the 1909 Nobel Prize in physics with Marconi for contributions to the radio art.

13 J. C. Bose, "On the Determination of the Wavelength of Electric Radiation by a Diffraction Grating," *Proc. Roy. Soc.,* v. 60, 1897, pp. 167–78.

14 For a wonderful account of Bose's work with millimeter waves, see David T. Emerson, "The Work of Jagadis Chandra Bose: 100 Years of MM-Wave Research," *IEEE Trans. Microwave Theory and Tech.,* v. 45, no. 12, 1997, pp. 2267–73.

15 Most scientists and engineers are familar with Rayleigh's extensive writings on acoustics, which include analyses of ducting (acoustic waveguiding) and resonators. Far fewer are aware that he also worked out the foundations for electromagnetic waveguides at a time when no one could imagine a use for the phenomenon and when no one but Bose could even generate waves of a high enough frequency to propagate through reasonably small waveguides.

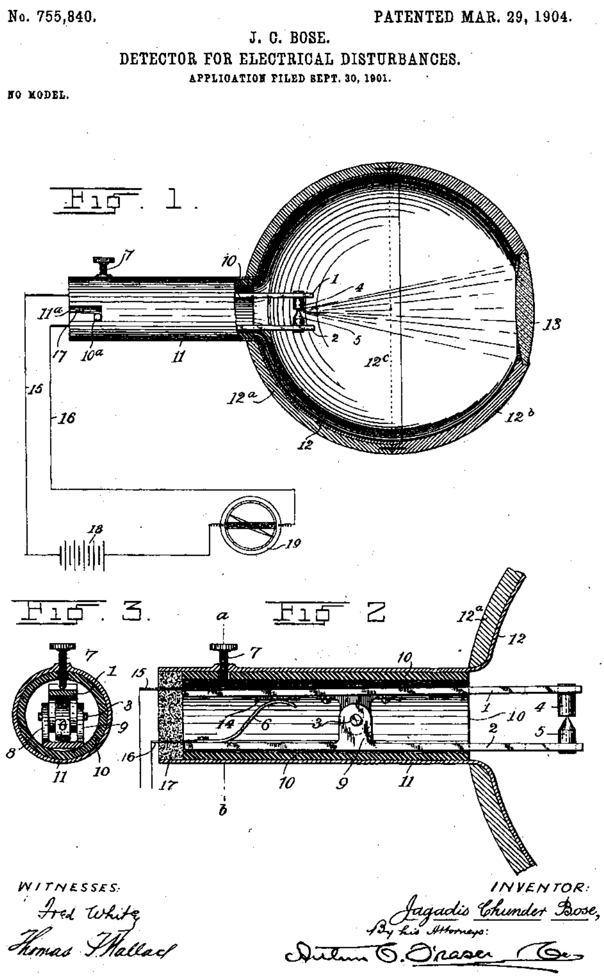

FIGURE 1.6. Bose's bolometer patent (first page)

This patent appears to be the first awarded for a semiconductor detector, although it was not explicitly recognized as such because semiconductors were not yet acknowledged as a separate class of materials (indeed, the word *semiconductor* had not yet been coined). Work along these lines continued, and General Henry Harrison Chase Dunwoody filed the first patent application for a rectifying detector using carborundum (SiC) on 23 March 1906, receiving U.S. Patent #837,616 on 4 December of that year. A later application, filed on 30 August 1906 by Greenleaf Whittier Pickard (an MIT graduate whose great-uncle was the poet John Greenleaf Whittier) for a silicon (!) detector, resulted in U.S. Patent #836,531 just ahead of Dunwoody, on 20 November (see Figure 1.7).

As shown in Figure 1.8, one connection consists of a small wire (whimsically known as a catwhisker) that makes a point contact to the crystal surface. The other connection is a large area contact canonically formed by a low–melting-point alloy

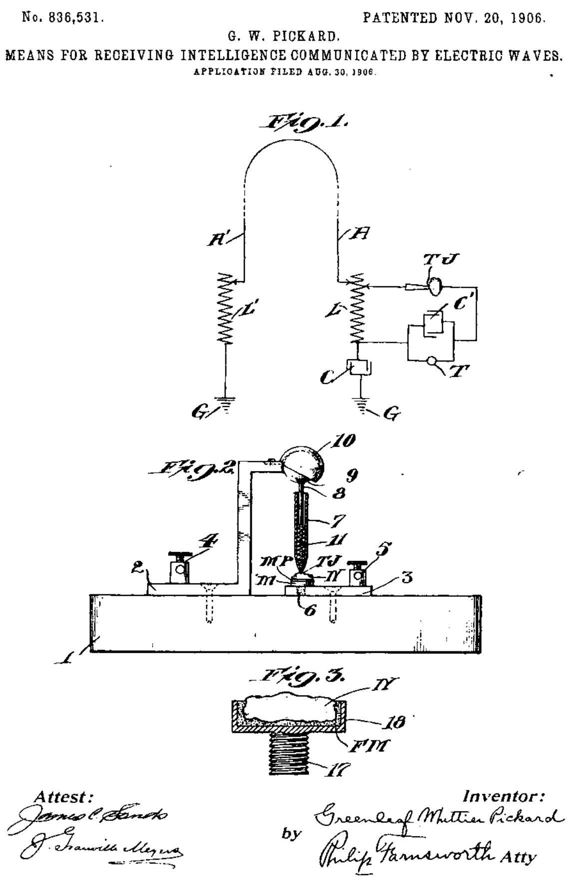

FIGURE 1.7. The first silicon diode patent

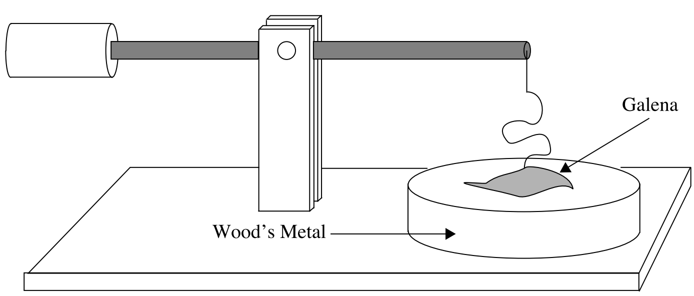

FIGURE 1.8. Typical crystal detector

(usually a mixture of lead, tin, bismuth, and cadmium known as Wood's metal, which has a melting temperature of under 80°C), that surrounds the crystal.[16] One might call a device made this way a point-contact Schottky diode, although measurements

[16] That said, such immersion is unnecessary. A good clamp to the body of the crystal usually suffices, and it avoids the use of toxic metals.

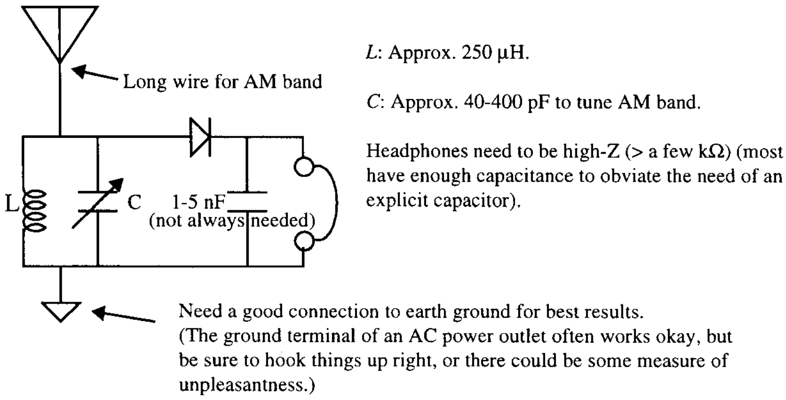

FIGURE 1.9. Simple crystal radio

are not always easily reconciled with such a description. In any event, we can see how the modern symbol for the diode evolved from a depiction of this physical arrangement, with the arrow representing the catwhisker point contact.

Figure 1.9 shows a simple crystal radio made with these devices.[17] An *LC* circuit tunes the desired signal, which the crystal then rectifies, leaving the demodulated audio to drive the headphones. A bias source is not needed with some detectors (such as galena), so it is possible to make a "free-energy" radio.[18] As we'll see, someone who had been enthralled by the magic of crystal radios as a boy would resurrect point-contact diodes to enable the development of radar. Crystal radios remain a focus of intense interest by a corps of dedicated hobbyists attracted by the simple charm of these receivers.

Pickard worked harder than anyone else to develop crystal detectors, eventually evaluating over 30,000 combinations of wires and crystals. In addition to silicon, he studied iron pyrites (fool's gold) and rusty scissors. Galena detectors became quite popular because they are inexpensive and need no bias. Unfortunately, proper adjustment of the catwhisker wire contact is difficult to maintain because anything other than the lightest pressure on galena destroys the rectification. Plus, you have to hunt around the crystal surface for a sensitive spot in the first place. On the other hand, although carborundum detectors need a bias of a couple of volts, they are more

[17] Today, *crystal* usually refers to quartz resonators used, for example, as frequency-determining elements in oscillators; these bear no relationship to the crystals used in crystal radios. A galena crystal may be replaced by a commercially made diode (such as the germanium 1N34A), but purists would disapprove of the lack of charm. An ordinary U.S. penny (dated no earlier than 1983), baked in a kitchen oven for 15 minutes at about 250°C to form CuO, exhibits many of the relevant characteristics of the galena (e.g., wholly erratic behavior). Copper-based currencies of other nations may also work (the author has verified that the Korean 10-won coin works particularly well). The reader is encouraged to experiment with coins from around the world and inform the author of the results.

[18] Perhaps we should give a little credit to the human auditory system: the threshold of hearing corresponds to an eardrum displacement of about the diameter of a hydrogen atom!

mechanically stable (a relatively high contact pressure is all right) and found wide use on ships as a consequence.[19]

At about the same time that these crude semiconductors were first coming into use, radio engineers began to struggle with the interference caused by the ultrabroad spectrum of a spark signal. This broadband nature fits well with coherer technology, since the dramatically varying impedance of the latter makes it difficult to realize tuned circuits anyway. However, the unsuitability of spark for multiple access was dramatically demonstrated in 1901, when three separate groups (led by Marconi, Lee de Forest, and Pickard) attempted to provide up-to-the-minute wireless coverage of the America's Cup yacht race. With three groups simultaneously sparking away, no one was able to receive intelligible signals, and race results had to be reported the old way, by semaphore. A thoroughly disgusted de Forest threw his transmitter overboard, and news-starved relay stations on shore resorted to making up much of what they reported.

In response, a number of engineers sought ways of generating continuous sine waves at radio frequencies. One was the highly gifted Danish engineer Valdemar Poulsen[20] (famous for his invention of an early magnetic recording device), who used the negative resistance associated with a glowing DC arc to keep an LC circuit in constant oscillation.[21] A freshly minted Stanford graduate, Cyril Elwell, secured the rights to Poulsen's arc transmitter and founded Federal Telegraph in Palo Alto, California. Federal soon scaled up this technology to impressive power levels: an arc transmitter of over 1 *megawatt* was in use shortly after WWI!

Pursuing a different approach, Reginald Fessenden asked Ernst F. W. Alexanderson of GE to produce radio-frequency (RF) sine waves at large power levels with huge alternators (*very* big, very high-speed versions of the thing that recharges your car battery as you drive). This dead-end technology culminated in the construction

[19] Carborundum detectors were typically packaged in cartridges and were often adjusted by using the delicate procedure of slamming them against a hard surface.

[20] Some sources persistently render his name incorrectly as "Vladimir," a highly un-Danish name!

[21] Arc technology for industrial illumination was a well-developed art by this time. The need for a sufficiently large series resistance to compensate for the arc's negative resistance (and thereby maintain a steady current) was well known. William Duddell exploited the negative resistance to produce audio (and audible) oscillations. Duddell's "singing arc" was perhaps entertaining but not terribly useful. Efforts to raise the frequency of oscillation beyond the audio range were unsuccessful until Poulsen switched to hydrogen gas and employed a strong magnetic field to sweep out ions on a cycle-by-cycle basis (an idea patented by Elihu Thompson in 1893). Elwell subsequently scaled up the dimensions in a bid for higher power. This strategy sufficed to boost power to 30 kW, but attempts at further increases in power through scaling simply resulted in larger transmitters that still put out 30 kW. In his Ph.D. thesis (Stanford's first in electrical engineering), Leonard Fuller provided the theoretical advances that allowed arc power to break through that barrier and enable 1-MW arc transmitters. In 1931, as chair of UC Berkeley's electrical engineering department – and after the arc had passed into history – Fuller arranged the donation of surplus coil-winding machines and an 80-ton magnet from Federal for the construction of Ernest O. Lawrence's first large cyclotron. Lawrence would win the 1939 Nobel Prize in physics with that device.