Feasibility and Design for micropower sharp infrared broadcast antennas

~~Feasibility and Design for Bush Microwave Ovens~~

Detailed Response to the caught zomb from *poly*

As described at www.zombal.com

Report by *dragozzine*

Darin Ragozzine, Ph.D.

Zomb Statement:

Theoretical and practical analyses are wanted for low-power devices able to broadcast sharp infrared lines from micron-scale metal shapes. Two questions need answering: 1) With radio broadcasting antennas, metal rods (half-wave dipoles) are activated to produce radio waves of wavelengths typically twice the length of the rods. If tiny rods (5 - 20 microns long) are fabricated and activated to act as antennas, will they produce infrared waves of wavelength twice the rod length? 2) How can such tiny rods be made and connected, for example can integrated-circuit manufacturing techniques be used to make infrared antennas on a chip? More information in the attached file ZBL140X.pdf.

[Information in ZBL140X.pdf]

Infrared radiation in the range of interest has a wavelength of 5-20 μm (microns or micrometres).
Here is a reference on radio broadcast antennas:
http://en.wikipedia.org/wiki/Antenna_(radio)
While there are broadband designs for antennas, the vast majority of antennas are based on the half-wave dipole which has a particular resonant frequency. At its resonant frequency, the wavelength (figured by dividing the speed of light by the resonant frequency) is slightly over twice the length of the half-wave dipole (thus the name). The quarter-wave vertical antenna consists of one arm of a half-wave dipole, with the other arm replaced by a connection to ground or an equivalent ground plane (or counterpoise). A Yagi-Uda array consists of a number of resonant dipole elements, only one of which is directly connected to the transmission line. The quarter-wave elements of a dipole or vertical antenna imitate a series-resonant electrical element, since if they are driven at the resonant frequency a standing wave is created with the peak current at the feed-point and the peak voltage at the far end.

Response

Abstract: Familiar antennas are devices that convert electromagnetic radiation (i.e., light) at radio wavelengths into electric signals and vice versa. The most efficient conversion is possible when the antenna has a size commensurate with the wavelength as this allows for resonant interaction between the incoming radiation and the electrons in the metal. Antennas are regularly found for radio and microwave wavelengths of a few centers to a few hundred meters, so the question is whether antennas can be “miniaturized” to work with light at much smaller wavelengths. Research online shows that this is plausible and that this is an active research area known as infrared microtransmitters, infrared microarrays, and nantennas. Based on this research, we can answer the questions posed by this Zomb. 1) The basic antenna conversion of electricity to light works at infrared wavelengths, but the main difficulties are with the efficiency of this conversion (skin effect) and with the associated electronics (high-frequency diodes). 2) Manufacture of such tiny structures is possible with a few different techniques (e.g., photolithography and/or electron beam lithography) that resemble integrated circuit designs.

Background

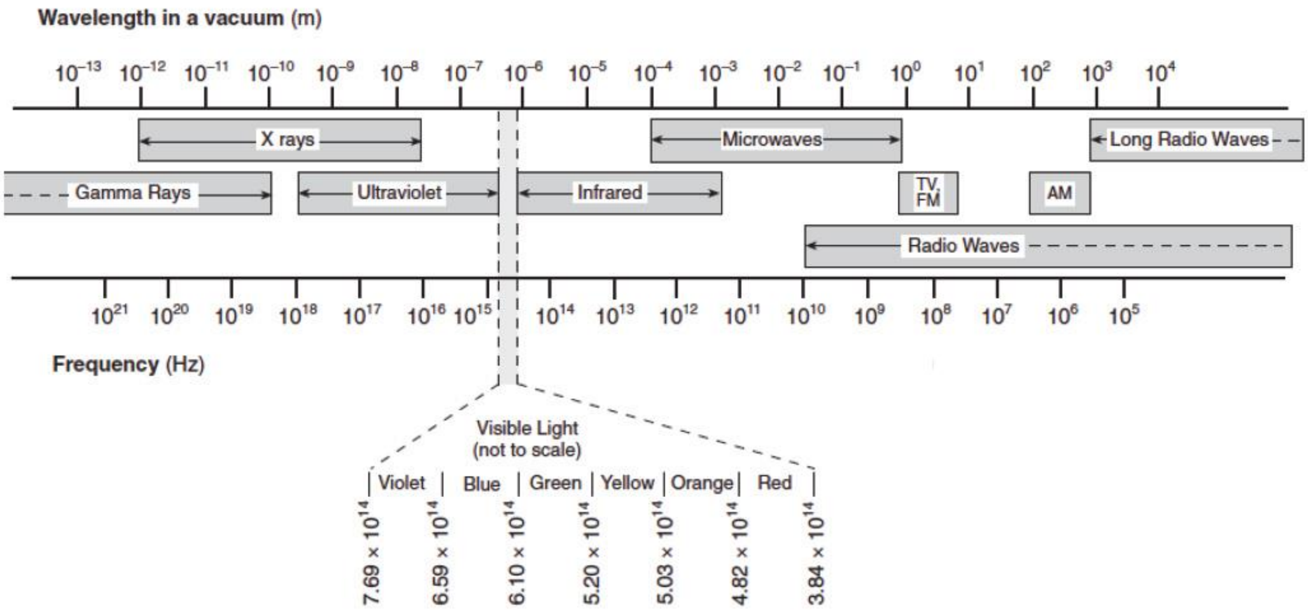
We begin by introducing some of the physics principles and concepts that we will need at a level appropriate for the lay reader. This section can be mostly skipped by those with familiarity with the relevant physics.

About 150 years ago, James Clerk Maxwell combined everything known about electricity and magnetism at the time into a small number of equations now known as Maxwell's Equations. The equations described the space and time variations of electric and magnetic fields. A field is like a function that describes the strength and direction of the electric or magnetic force that would be felt by a charged particle at any point in space. Maxwell and those before him noticed that the laws of physics include the rule that changing electric fields create magnetic fields and changing magnetic fields create electric fields. Maxwell's Equations made it straightforward to determine that there was a stable "wave" solution where an oscillating electric field created an oscillating magnetic field which then propagated the oscillating electric field which then propagated the oscillating magnetic field, etc. These "electric and magnetic" waves oscillate at the same frequency and, like waves on water, carry energy with them in a particular direction. These electromagnetic waves are no magic mathematical trick… but are part of our everyday experience under what we call "light".

Light that we can see with our eyes (visible or optical light) is composed of electromagnetic waves. All light travels at the speed of light (which can be modified depending on the electromagnetic interactions of the material that the light is traveling in) which is approximately 300,000 km/s, unimaginably fast. When a wave's speed is known, there is a relationship between the wavelength of the wave (e.g., the size of the wave from crest to crest) and the frequency of the wave (e.g., how many times a fixed observer would see the wave move up and down per second). Though sometimes different symbols are used, the equation is $c = \lambda\nu$ where c is the speed of light λ is the wavelength and ν is the frequency.

It turns out that Maxwell's equations were really only an approximation to the quantum mechanical description which uses wavefunctions to capture the wave nature of light, but can also explain why light appears to act like discrete particles in some circumstances. For our purposes, introducing quantum effects is not necessary for the vast majority of our discussion, so we will focus more on classical electromagnetic waves.

Once a full appreciate of light as a wave was realized, scientists noticed that visible or optical light only spanned a short portion of all the possible forms of light. William Herschel had earlier noticed that there was some kind of invisible light, by taking a prism and placing a thermometer in the region beyond where the red part of light landed. The thermometer warmed up, incidating the transfer of energy. This "beyond red" light is called infrared and our skin is sensitive to such light, which we "detect" as heat. The electromagnetic spectrum (see Figure) shows the wide variety of all possible wavelengths of light and their common names today. It is quite remarkable that "visible light" only indicates a very small portion of this spectrum. Generally speaking, in non-visible wavelengths, physicists often refer to light as radiation. (Radiation has a negative denotation from radioactive materials, some of which emit particles or light that is biologically harmful. While some short wavelengths of light are to be avoided, most radiation is not energetic enough to be harmful in typical doses.) We will also note here that the energy in light is proportional to its frequency (and thus inversely proportional to wavelength). This makes sense, a wave that moves up and down faster contains more energy.



Because radiation is really an oscillating electromagnetic field, when radiation impinges on matter, it provides oscillating electrical forces. (The electric field strength is directly proportional to the electric force on charged particles.) How this light interacts with matter depends on the properties of the matter. Here, we will focus on antennas which are made of metals which are near-perfect conductors of electricity. Metals are good at conducting electricity because the electrons associated with the atoms in the metal are virtually completely free to move from one atom to another. So, if an electric field comes along with its associated electric force, there is a minimal "friction" or opposing force to prevent the electrics from being pushed around by the electric field. In the case of an oscillating electric field (i.e., radiation), the electrons in the metallic conductor are made to oscillate at the same frequency and with similar wavelength.

In many areas of physics, there is a property called "resonance" which describes two frequencies that are equal (or even multiples of one another). When two objects are in resonance, they efficiently "couple", i.e. energy can be efficiently transferred from one to the other. Non-resonant interactions are weaker because the two components are usually "out-of-sync". Hence, we refer to "resonant enhancement" that occurs when two frequencies are "in sync".

In the case of radiation and metals, the most efficient energy transfer is possible when the wavelength of the radiation has a specific size relative to the size of the metallic conductor. When these have a special relation, then the radiation can be efficiently transferred into the motion of electrons within the metal. Metallic conductors that are designed to be a specific shape to efficiently couple to radiation are called "antennas". In the simplest antenna, the half-wave dipole, a metallic rod with half the wavelength of the desired radiation is used. As the electric fields from the impinging radiation move the electrons around, the electrons of the whole antenna move at the same frequency and there is a resonant enhancement in the ability to absorb the radiation.

Note that resonant enhancement can be “sharp” on the resonance (e.g., you have to be really close to the resonance to see much enhancement) or more diffuse (e.g., even being kinda-near resonance still provides a significant benefit). Part of antenna design includes choosing not only a specific wavelength for the resonance, but also to determine how sharp/diffuse the antenna should be in accepting radiation. Typically, sharp resonant enhancement is stronger than diffuse enhancement, so this is an important antenna design decision. Antennas are typically characterized by “gain”, the efficiency at which radiation is turned into moving electrons. Gain is a function of frequency (due to the resonance) and a function of direction. (If an incoming wave generates electric field oscillations parallel to the direction of the long antenna, the efficiency is high; if it’s perpendicular, then the efficiency is low.)

This entire process also works in reverse. Moving the electrons in an antenna at a specific frequency will generate oscillating electric and magnetic fields at the surface of the antenna. These generate electromagnetic radiation which is now being efficiently emitted from the antenna. The physics is the same either way, so antenna gain can refer both to the receiving and transmitting modes.

Some of the additional physics background will be discussed more fully below. Here I will mention that antennas have shown that there is an efficient way to convert radiation into moving electrons. These moving electrons will typically be found only near the outer surface of the conductor (called the “skin”). Furthermore, just having moving electrons is only the first step. Typically, the next step is to take these moving electrons and refer to it as an electrical signal.

Since the electrons are moving back and forth, this is called an “Alternating Current” or AC electrical signal. This is contrasted with electrons moving in one direction, e.g. “Direct Current” or DC, which is generally needed to transmit this electricity from the antenna to somewhere else (e.g., the circuitry that interprets the electrical signal to provide you with WiFi). Hence, it is critical to include an additional component which converts AC signal to a DC signal. This is done with a “diode” which is an semi-conductor organized in such a way to be similar to a one-way valve. This one-way valve takes the AC signal and, by only accepting energy in one direction, turns it into a more-DC like signal. In practice, the process of converting AC to DC involves complicated circuits, but the central component to all of these is a diode of some kind.

Interaction of Light and Matter at Different Frequencies

The properties of electromagnetic radiation, resonance, electrical signals, and antennas described above are generally physical principles that do not depend on size. Theoretically, antennas can be used for any kind of radiation seen in the electromagnetic spectrum (see Figure above). Practically, however, there are some serious issues.

First, for the most energetic light, it is not plausible to build antennas in the typical sense. Recall that frequency is proportional to energy and that wavelength is inversely proportional to frequency then clearly gives that high energy light has very short wavelengths (see Figure above). For example, X-rays are quite energetic and have tiny wavelengths around 10^{-10} m or the size of a single atom. At these size scales, light and matter can interact, but not in the traditional sense of “generating electricity”.

Even optical light has wavelengths around 10^{-7} m or the size of molecules with ~dozens of atoms. At this scale, we do indeed have antennas that are good and emitting and transmitting light at specific frequencies. These antennas are called photosensitive chemicals and include carotene-related molecules at the back of your eyes that allow you to see, the chemicals used in photographic film, and "dyes" which are chemicals that are designed or selected to transmit specific colors.

While visible light can be used to transfer radiation into electrical energy, e.g., standard photovoltaic cells (solar panels), the physics behind this process is not like the physics of an antenna. For example, in a photovoltaic cell, the incoming light does not oscillate the electrons back and forth, rather the light gives all of its energy to a ~single electron which then has enough energy to move freely and follows the current of the other electrons moving in the material. Another way to note the difference is to realize that photovoltaics are made out of semi-conductors (like silicon) whereas antennas are made of conductors (like metal). While semi-conductors can also be used to convert electricity into light (in the form of LEDs, light-emitting diodes, a diode is semi-conductor device), there is generally little fine control over the frequency and intensity of light that can be emitted; whereas an antenna can emit radiation with enough flair to transmit millions of pieces of information per second (e.g., wireless devices).

Antennas work well at microwave and radio wavelengths, allowing for the efficient coupling of radiation and electrical signals for wavelengths from ~1 cm to kilometers. These wavelengths are also associated with "low" frequencies (see Figure above) of 10^6 to 10^9 cycles per second (e.g., MegaHertz and GigaHertz or MHz and GHz). At these frequencies, there already exist many diodes which can convert the AC signal into a DC signal without much loss of efficiency or energy.

Far-Infrared Radiation

The Zomb is focused on a specific region of electromagnetic radiation generally known as "far-infrared" or FIR. We will assume a typical wavelength of 10 microns, which corresponds to a frequency of 3×10^{13} Hz or 30 TeraHertz or 30 THz.

One can use properties similar to solar panels to convert infrared light into electricity. Astronomers are experts at this process, using either modified semi-conductors or devices called "bolometers" which basically detect light by observing an increase in energy/temperature.

FIR Antennas would be miniaturized extensions of microwave antennas that are commonly in use. These have been studied extensively as can be found with Google searches for "infrared microtransmitter" (ignoring transmitters in remote controls, which don't use antennas but rather a Morse-code-like method for transferring information), infrared microarrays, or nantennas (short for "nano antennas").

There is significant scientific and engineering development of such devices for multiple potential uses. One example is a "nantenna" that could be used to convert radiation into electricity for power purposes. Although the real promise would be in capturing optical light, this is much harder, so the pathway to developing such techniques starts with building antennas in the FIR range. Another powerful driving force is the fact that using light of higher frequencies allows for more information to be transferred. Short range ultra-high transmission speeds are thus possible with FIR antennas that are unheard of with traditional microwave or radio antennas. (See, e.g., http://www.techpowerup.com/155626/new-

microtransmitter-can-oscillate-in-fir-band-promises-dozens-of-gbps-of-bandwidth.html)
The practical creation and use of these antennas can be described by answering the two questions associated with this Zomb.

1. If tiny rods (5 - 20 microns long) are fabricated and activated to act as antennas, will they produce infrared waves of wavelength twice the rod length?

As mentioned above, the basic physics of antennas does not depend on scale. If 10 micron long rods could be created and the electrons in them could move at the 30 THz frequency, then it would generate FIR radiation due to the resonance in the size of the object and the frequency of the light.

There are at least two problems that arise at the FIR size scale that are difficult to manage. These are discussed in the Wikipedia: Nantenna page.

The first is related to the fact that the AC currents moving within a conductor tend to concentrate near the surface of the conductor. The reason for this is complex to explain (see Wikipedia: skin effect), but it is related to the fact that the AC electrical currents create magnetic field variations which are harder to maintain in the center than at the edges. It turns out that the concentration is stronger for higher frequencies, so at FIR frequencies, almost all of the electricity is at the very surface of the conductor. This reduces the effective cross-section of the conductor and also leads to more complex effects since the region carrying the most electricity is now small enough for the effects of individual atoms to begin to be apparent. Increasing the size of the antenna can help with this effect, but reduces the efficiency of the antenna due to edge effects (discussed more below). So, this is a serious issue.

The other issue is the conversion of the electrical signal from AC to DC (in the case of using the antenna as a receiver) or converting from DC to AC (in the case of using the antenna as a transmitter). The frequency of FIR radiation is 30 THz or 30,000,000,000,000 oscillations per second. At this frequency, standard diodes do not work and new research is needed to make this process reasonably efficient. The website referenced above (http://www.techpowerup.com/155626/new-microtransmitter-can-oscillate-in-fir-band-promises-dozens-of-gbps-of-bandwidth.html) included a group that claimed to solve this problem by using a fundamentally different kind of diode (that employs more quantum mechanical effects).

Although I didn't research this out specifically, I suspect that not all of the types of antennas used for radio/microwaves can be used directly for FIR radiation.

2. How can such tiny rods be made and connected?

Extremely small structures can be created on silicon wafers in the form of integrated circuits. Using this technique to make antennas relevant to the sizes for FIR light would be more-or-less straightforward. However, these manufacturing processes are used on *semi-conductors* and not on *conductors* that would be needed for antennas.

One reason why antennas are much longer than the radius of the metallic conductor is to minimize/avoid so-called "edge effects" that occur in the real world. For example, if an antenna was a wide as it was long, different electrons in the antenna would be moving at different times, nearly canceling the resonant effect that the antenna is supposed to provide. For this same reason, FIR antennas would need to have elongated shapes of perhaps ~10 microns long, but only ~0.3 micron radius. The distance between the conducting element also need to be at least a few wavelengths away from other conductors (except in the case of more complex antenna arrays), to avoid similar "edge"-like effects. Thus, while the antennae themselves are 10 microns long, manufacturing them requires a sub-micron precision.

Creating metallic (conducting) antenna structures at the ~micrometer scale is plausible with certain manufacturing techniques, some of which bear similarities to semi-conductor manufacturing. I'll mention here "photolithography" and "electron beam lithography". Both of these work in the same way, with photolithography employing light and electron beam lithography employing electrons. The technique works by starting with a base called the "substrate", usually of silicon. Then, a thin vapor film deposition process is used… basically metal is vaporized to become a gas and then is allowed to condense on the substrate similar to how dew or frost covers the ground with a thin nearly-uniform layer of metal. Then, using concentrated light or electrons, the portions of the metal that is not wanted is removed, similar to chiseling away the unwanted stone from a sculpture, hence the use of the word "lithography" which indicates engraving into stone. Typically, the light/electrons significantly weaken the parts that are to be removed and then some chemical processing is used to actually remove that material. Photolithography can have a precision of 0.05 micrometers and electron beam lithography can be ~5 times more precise.

With the ability to create metallic components using a chisel of size 0.05 micrometers, state of the art engineering techniques make it plausible to create the physical structures associated with a 2-dimensional FIR antenna. Like circuit board production now, this could theoretically be scaled up to factory-level production with associated decreases in cost.

Conclusions

First, I introduced the background of light, it's interaction with conductors, and the properties of antennas. Far-infrared (FIR) antennas that operate on similar principles to larger microwave/radio antennas are theoretically quite possible. Practically speaking, while technology exists that could create certain versions of such antennas, there are some major bottlenecks in the efficiency due to the "skin effect" and the lack of electronics that can handle the extremely high frequencies (THz) associated with this kind of light.

I believe that the above answers the questions posed in this Zomb, along with given significant explanation. Please let me know if any of the above arguments are unclear or if you have any other questions or zombs. Doing a Google or Wikipedia search on most of the above concepts will provide helpful insights and references. Other bibliographic citations are available upon request.

Thank you for this opportunity.

Dr. Ragozzine is a Postdoctoral Researcher in the Astronomy Department at the University of Florida. He is currently funded by the United States National Aeronautics and Space Administration (NASA) to

work on the NASA Kepler Space Mission. This document is his personal composition and reflects his personal opinion, not that of the University of Florida, NASA, or any other party. He has many years of research experience in the orbital dynamics of planetary systems, the Kuiper belt within our own solar system, and extra-solar planets observed around other stars.