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Microwave Memos

Memo 2

The Phaser

Foreword

phaser (noun)(plural phasers): one that phases

phase (transitive verb): (1) to adjust so as to be in phase

phase (noun): (3) the point or stage in a period in uniform circular motion, simple harmonic motion, or the periodic changes of any magnitude varying according to a simple harmonic law (as sound vibrations, alternating currents, or electric oscillations) to which the rotation, oscillation, or variation has advanced considered in its relation to a standard position or assumed instant of starting and expressed in angular measure with one cycle or period being 360 degrees

in phase (adverb phrase): (1) in or of the same phase

from:

Webster's Third New International Dictionary of the English Language Unabridged, 1967

Pulsed
High
Amplitude
Sinusoidal
Electromagnetic
Radiation

Yours truly

"Diplomats! The best diplomat I know is a fully activated phaser bank."

Lt. Cmdr. Montgomery Scott
Starship Enterprise
Star Trek episode: "A Taste of Armageddon"

Capt. James T. Kirk: "If I only had some phasers ..."
Lt. Cmdr. Montgomery Scott: "Phasers! You've got them. I have one bank recharged."
Capt. James T. Kirk: "Scotty! You've just earned your pay for the week. Stand by."

Star Trek episode: "The Doomsday Machine"

I Introduction

In [2] I discussed the various elements of maximizing the electromagnetic response of a target considering the source, antenna, propagation, coupling to the system exterior, and transfer function to the system interior. The conclusion was that the optimum frequency to maximize the response of the target interior electrical ports was around a GHz. The exact frequency depends on measurement of the transfer function from an incident plane wave to the interior port of interest, and selection of an appropriate resonance maximum of this transfer function. In [4] I discussed some of the elements in a program to develop an HPM weapon. In that memo I pointed out the importance of low level CW measurements on real systems (full systems, not components or subsystems) to obtain these transfer functions and thereby find the important weapon frequencies for given targets (ours and theirs).

This memo is devoted to the design of a canonical high power microwave (HPM) weapon consisting of the microwave source (including in principle the power supply) and radiating antenna system. I shall refer to this as a phaser; this is a weapon, not merely a jammer, or even a radar. (As you may imagine, keeping things in proper electrical phase is an important part of the source and antenna design.)

Let us first fix the frequency as 1.00 GHz. This is as good a choice as any considering the current state of knowledge of target response. One could repeat the calculations for say 500 MHz and 2.00 GHz if one wanted a set of phasers at different frequencies. One may desire some frequency agility in a phaser, but the first problem is to make it have a high power with some attention to pulse width.

Having selected 1.00 GHz we can next choose the waveguide(s) for taking the microwave from one or more sources to one or more antennas. Choose standard rectangular waveguide with a 2:1 dimension ratio for good bandwidth in the lowest order mode ($H_{1,0}$ mode) and good power handling capability. Let the operating frequency be near the upper frequency limit (cutoff frequency of the next modes (twice the cutoff frequency of the $H_{1,0}$ mode for a rectangular guide)). This maximizes the waveguide cross section dimensions and thereby maximizes the power handling capability.

A standard waveguide for this purpose is:

designation:	WR 975
	RG-204/U
	WG-4 (British standard)
	R6 (IEC)
inside dimensions:	.248 m × .124 m
cutoff frequency for $H_{1,0}$ mode:	.606 GHz ($\lambda = .495$ m)
lowest cutoff frequency for higher order modes:	1.21 GHz ($\lambda = .248$ m)
nominal frequency range:	.75-1.12 GHz

Assuming that this waveguide is operated under high vacuum conditions so that field emission from the walls is the limiting factor such as waveguide should be capable of handling over a TW. This is a very high power level (whether peak or average) which has not yet been experimentally obtained so details involving power, pulse width, flanges, etc., need to be explored.

Depending on the details of the microwave source there may be various signals present in various modes of one or more waveguides (including possibly coax). These can be converted to the more suitable $H_{1,0}$ mode of a rectangular waveguide.

Having defined this waveguide then the corresponding vacuum flange serves as a universal interface between microwave source and antenna system. There may be only one waveguide in the case of a small phaser, but there may be many in larger designs. In a space-based phaser a hard vacuum is already present, simplifying the antenna system design. In an atmospheric-based phaser the waveguides in general will be expanded and transitioned with dielectric windows to air, perhaps with an intermediate section of SF_6.

This definition of a waveguide interface is useful in that various sources and antenna systems can be interchanged as design improvements are made. The two are quite separable. Further evolution may lead to other considerations, e.g. circularly polarized waves for slightly higher power when coming out to air. Such could alter the waveguide interface. However, for initial purposes a simple rectangular guide (or guides) seems appropriate.

II Single Microwave Source

As discussed in [4] the leading candidates for HPM sources involve some variation on the magnetron theme. We need lots of power and high efficiency. Magnetrons have operated in the past with about 30% efficiency and at these high powers relativistic magnetrons have already attained about 10% efficiencies [6] (defined in terms of average microwave power). In the π mode about

1.8 GW average power (averaged over one cycle, peak power being about twice this) has been obtained at about 2.8 GHz [5]. Efficiency is very important as one goes to very high energies in the microwave pulse since the energy from the pulser driving the microwave source is greater than the microwave energy, and the difference of the two energies is dissipated as heat. In the case of a magnetron the energy difference is deposited as heat in the anode, and similar problems occur in other microwave sources.

If one extrapolates from published results on the A6 magnetron in [5,6] in going from 2.8 GHz to a larger (about 2.8 times larger in linear dimensions) magnetron operating at 1.00 GHz one might expect about 10 to 15 GW average power (or peak power in the 20 to 30 GW range). This is a scaling based on anode (or cathode) area (or λ^2 if you will). Of course the pulse power has to be scaled up accordingly and there is some uncertainty in magnetron design. Perhaps it will take a few attempts to reach this level.

An optimized single magnetron such as this might be part of a miniphaser, but seems also to be a logical step in magnetron development. In itself it is not necessary that this be an amplifier of some reference 1.00 GHz signal; it can be an oscillator. However, for the next step an amplifier (or better, phase-controlled oscillator) would be useful. For this purpose one may wish to bunch the electron beam using a low level signal (much as in a Klystron amplifier) but still have a magnetic field guiding the beam into magnetron-like cavities to extract the energy. So a hybrid gyrotron/magnetron concept may be useful.

Now one may advocate another type of microwave source at 1 GHz. There are various candidates that have been suggested. First, however, let us only consider things with both high power and high efficiency, such as discussed here. Second, let us consider hard data and not just claims. Independent verification would be useful. I see a big NIH (not invented here) factor. Responsible scientists/engineers are supposed to be able to make objective judgments concerning technical matters within their fields. So what if something useful is invented somewhere else! Use it and/or build on it to make something even better! Ethics for scientists and engineers are not the same as for lawyers who can rightly be paid to argue on any side of any question.

If, as seems to currently be the case, magnetrons are the best (or even at least one of the best) candidates for our HPM source, why not have several groups working on them. Let data be freely exchanged among the groups and let the investigators be required to defend their results in front of their peers.

III Multiple Phase-Locked Microwave Sources

As one makes larger and larger microwave sources one may decide after a while that he is beating a dead horse and it is time to take another tack. How about multiple sources?

Well, the problem here is phase locking the N sources together. This is essential if we are to get the maximum effect at the target. If the N sources are combined in the same single waveguide feeding the same antenna (and no nonlinear limitations apply in the circumstances) then the powers can be added (provided proper matching is used). If N separate identical antenna systems are used then the incident fields can be added at the target, the associated local power density (not total power) goes like N^2 at the target.

Of course, it is not obvious that a particular microwave source that is optimum in the sense for a single source (section 2) is optimum for multiple-source use here. If the single source operates as a phase-controlled amplifier of some low-level exciting microwave signal, then this same low-level signal can be used to control N sources (perhaps after amplification). Then we have the option of combining the powers of the various sources in phase into one antenna system or many (say N or some integer fraction of N as applicable).

While a magnetron source seems appropriate in current technology for a single source, it is less obvious that it is most appropriate for a multiple source. This does not mean that something else is currently obviously more appropriate. Considerable work is needed here. How does one phase control a magnetron (or any other *comparable* high-power source for that matter)?

In any event the step to multiple phase-controlled sources is a major step. While for a single source we may be looking for say 10 to 15 GW average power (a mini-phaser) the full phaser may be a more appreciable fraction of a TW (say .1 TW or even larger). One may envision, say six sources, in a Colt arrangement around a single controlling source, each source feeding out on a rectangular waveguide to the feed system to a reflector antenna. Alternately N sources may be widely spaced with separate antennas, albeit all phase locked to the target.

IV Canonical Phaser

For later calculations and scaling purposes let us now define a canonical phaser. Considering the previous sections let this be 1 GHz and .1 TW average power. The radiated energy depends on the pulse width which does not enter significantly into our present discussions, but does have some influence on the target interaction in the 2-norm sense [2,3]. A pulse width of .1 μs corresponds to 10 kJ and 1 μs to .1 MJ (assuming a rectangular pulse (envelope)). Referring to [2] we have

$$\begin{aligned}
P_{\text{avg}} &= .1\ \text{TW} \\
P_0 &= 2P_{\text{avg}} = .2\ \text{TW} \\
P_0 &= \frac{E_0^2}{Z_0}A = \frac{V_0'^2}{Z_0} \\
A &\equiv \text{antenna aperture area} \\
Z_0 &\equiv \text{impedance of free space} \simeq 377\Omega \\
E_0 &\equiv \text{peak electric field on aperture} \\
& \quad\ \text{(in outgoing wave)}
\end{aligned}$$

$$\begin{aligned}
& \quad \text{(approximated as uniform over aperture)} \\
V_0' &\equiv \text{equivalent peak voltage of source} \\
&= \sqrt{Z_0 P_0} \simeq 8.68 \text{ MV} \\
&= E_0 A^{1/2}
\end{aligned}$$

The antenna systems for such a phaser are discussed in subsequent sections. They are somewhat varied depending on application. The reflector area and single versus multiple antenna systems are parameters to be chosen.

V Single Reflector Antenna

At least in the atmosphere the basic antenna limitation is electrical breakdown. Defining

$$\begin{aligned}
E_0 &\equiv \text{peak electric field} \\
Z_0 &\equiv \text{impedance of free space } \simeq 377\Omega \\
A &\equiv \text{area of aperture plane of reflector} \\
P_0 &\equiv \text{peak power (total)} \\
&= 2\, P_{\text{avg}} \\
P_{\text{avg}} &\equiv \text{average power (the normally used} \\
& \quad \text{measure of microwave power)} \\
p_0 &\equiv \text{peak power per unit area} \\
&= 2\, p_{\text{avg}} \\
p_{\text{avg}} &\equiv \text{average power per unit area}
\end{aligned}$$

we have the relations

$$\begin{aligned}
p_0 &= \frac{E_0^2}{Z_0} = 2\, p_{\text{avg}} \\
P_0 &= p_0 A \\
P_{\text{avg}} &= p_{\text{avg}} A
\end{aligned}$$

This assumes negligible losses in going from the source through the antenna system. Assuming that at sea level we operate at a nominal 1 MV/m for E_0 in the aperture plane (outgoing wave from the reflector) then we have

$$\begin{aligned}
p_0 &= 2\, p_{\text{avg}} \simeq 2.65 \text{ GW/m}^2 \\
p_{\text{avg}} &\simeq 1.33 \text{ GW/m}^2
\end{aligned}$$

Assume a circular disk of radius a for the aperture so that

$$A = \pi a^2$$

Than taking a small phaser (say 25 GW avg.) the minimum antenna aperture has

$$\begin{aligned} A_{\min} &\simeq 75.2 \text{ m}^2 \\ a &\simeq 4.89 \text{ m} \\ 2a &\simeq 9.78 \text{ m (diameter)} \end{aligned}$$

Recall from [1,2] the result for the electric field away from the antenna aperture

$$\begin{aligned} E_f &\simeq E_0 \frac{\omega_s A}{2\pi c R_0} = E_0 \frac{f_s A}{c R_0} = E_0 \frac{A}{\lambda_s R_0} \\ &\equiv \text{peak field away from antenna} \\ f_s &\equiv \text{frequency } = \frac{\omega_s}{2\pi} = \frac{c}{\lambda_s} \simeq 1 \text{ GHz} \\ \lambda_s &\simeq .3 \text{ m} \\ R_0 &\equiv \text{distance of observer from aperture} \end{aligned}$$

This is not just a far-field result because the aperture is assumed to be focused at the observer [1]. This merely requires that (for on-axis results)

$$\begin{aligned} R_0 &\gg a \\ R_0 &\gg \lambda_s \end{aligned}$$

The power incident at the observer is (local plane-wave approximation)

$$\begin{aligned} p_f &\simeq \frac{E_f^2}{Z_0} \\ p_{f_{\text{avg}}} &= \frac{1}{2} p_f \end{aligned}$$

A. 100 m^2 canonical antenna

Let us then define a few canonical reflector antennas. First let us take (consistent with the canonical .1 TW avg. power)

$$\begin{aligned} A &= 100 \text{ m}^2 \\ a &\simeq 5.64 \text{ m} \\ 2a &\simeq 11.3 \text{ m (diameter)} \\ p_{\text{avg}} &= 1 \text{ GW/m}^2 \\ p_0 &= 2 \text{ GW/m}^2 \\ E_0 &\simeq .868 \text{ MV/m} \end{aligned}$$

Consider fields and powers at various distances:

R_0	E_f	$p_{f_{\text{avg}}}$
1 km	.289 MV/m	.111 GW/m^2
3 km	96.4 kV/m	12.3 MW/m^2
10 km	28.9 kV/m	1.11 MW/m^2
30 km	9.64 kV/m	.123 MW/m^2
.1 Mm	2.89 kV/m	11.1 kW/m^2

Note at distances sufficiently close to the antenna the focusing can make the air break down.

B. 10^5m^2 canonical antenna

Before you think this number is a jest, consider that such a reflector already exists at Arecibo. You see, reciprocity applies, and the radio-astronomy people understand quite well that large reflectors are good to have. While the example has a spherical rather than a parabolic reflector one can design the feed system to compensate for this [7].

Then let us take (consistent with the canonical .1 TW avg.)

$$\begin{aligned} A &= .1 \text{ Mm}^2 \\ a &\simeq .178 \text{ km} \\ 2a &\simeq .357 \text{ km (diameter)} \\ p_{\text{avg}} &= 1 \text{ MW/m}^2 \\ p_0 &= 2 \text{ MW/m}^2 \\ E_0 &\simeq 27.5 \text{ kV/m} \end{aligned}$$

Consider fields and powers at various distances:

R_0	E_f	$p_{f_{\text{avg}}}$
10 km	.915 MV/m	1.11 GW/m^2
30 km	.305 MV/m	.123 GW/m^2
.1 Mm	91.5 kV/m	11.1 MW/m^2
.3 Mm	30.5 kV/m	1.23 MW/m^2
1 Mm	9.15 kV/m	.111 MW/m^2
3 Mm	3.05 kV/m	12.3 kW/m^2
10 Mm	.915 kV/m	1.11 kW/m^2
30 Mm	.305 kV/m	.123 kW/m^2

These fields are strong enough to break down the upper atmosphere if one is shooting upwards. Then there is the ionosphere and its associated dispersion. (This may also be a situation calling for some change in the operating frequency to greater than 1 GHz.) Note that for each distance in the table the antenna is refocused, so this does not represent the falloff of a single beam with distance.

VI Separated Multiple Reflector Antennas

Suppose we have the problem that our phaser beam is too powerful for the intervening medium at some intermediate distance between the antenna and target. Then we need to spread out the beam at this intermediate distance to get the electric fields down to avoid breakdown. However, we still want large fields at the target.

One can always increase the aperture area. For sufficiently large R_0 the focus is effectively at ∞ and the beam is a pencil beam with E_f like E_0 out to some distance of the order of A/λ_s, after which it diverges. This implies getting E_0 way down which may make A too large to be practical for .1 TW.

An alternate approach is to take the desired area A (and hence also E_0 for a given P_0) and divide it among N separated reflector antennas. Then space these reflectors so that the beams do not overlap significantly until one is past any region of concern in the upper atmosphere. These sources may be spaced many km apart depending on the specific choice of parameters. Beginning with total area A we have

$$\begin{aligned} A/N &= \text{area of individual reflectors} \\ P_0/N &= \text{power from each antenna} \\ A/(\lambda_s N) &\simeq \text{distance out to which each} \\ & \quad\text{``subphaser'' has a pencil beam} \end{aligned}$$

So far our primary consideration on the antenna design has been to maximize the signal at the target (in the center of the beam). In the case of separated subphasers the characteristics of the outer edge of the beam (sidelobes, etc.) will have some significance because of the overlap of adjacent beams.

Such distributed arrays of reflector antennas are quite possible. Just look at VLA! Even larger spacings are possible as in VLBI (very long baseline interferometry) where the relative phase between receiving antennas can be measured and controlled for data processing on a global scale. Atomic clocks, delay measurements, etc. are up to the accuracy required for establishing a phase controlled sinusoidal signal (the master phase controlled signal to be amplified at each subphaser).

One might envision some pattern of periodic equilateral triangles with subphasers at the corners as some closest packing configuration. This also can be thought of as a hexagonal pattern. Imagine six subphasers around some central control (with perhaps another subphaser) as some elementary array. (It looks like the chamber of a six gun pointing upward.)

VII Waveguide/Antenna Feed

In going from the interface discussed in section 1 we have one or more rectangular waveguides operating under high vacuum conditions. If one had a phaser on a space platform one could use the vacuum of space throughout the antenna system to achieve the required high electric-field breakdown conditions. In the atmosphere the problem is more difficult in that the extremely high fields in the waveguide(s) have to be reduced (by spreading out the energy) to a level that the air (assumed at sea level for the moment) can take.

Considering one of the waveguides this can be transitioned to a horn (or, if you prefer, a conical waveguide). As the wave propagates in the cone the fields decrease as the cross section dimensions increase. At some length the fields are low enough to be transitioned through a dielectric window to another medium such as air. Alternatively this might be some high-dielectric strength gas such as SF_6 so as to minimize the required horn size. After the beam has propagated in SF_6 and perhaps been reflected by a secondary reflector there may be another transition to air, either before or after the beam is reflected by the primary reflector.

There are various types of horns to consider. For a single horn one set of considerations will apply which may lead to, say, a circular cross section. For an array of horns (from an array of waveguides) one may choose a rectangular or diamond shape for the cross section so that the array of horns more efficiently fills up the horn-aperture surface (or perhaps feed surface) with the field distribution. There are also various types of lenses one may wish to consider with the horns to control the phase on the feed surface.

VIII Concluding Remarks

Well, this has covered a lot of ground. There are many design details to be optimized for each of the phaser designs for various applications (involving target, range, etc.). While we need lots of microwave power, it seems that antenna design is just as important. Reflector area is an extremely important parameter. (Perhaps the same reflectors could be used for the target acquisition radar.)

Defining some sort of simple interface between source and antenna allows for some independence in source and antenna development. This interface is some waveguide or set of waveguides under high vacuum conditions for maximum power transmission at microwave frequencies. Initially a rectangular guide seems appropriate, but future developments as for circular polarization may be appropriate later.

Note that the antenna system does not in general have 100% efficiency. The feed system which illuminates the primary reflector does not uniformly fill the primary reflector with all the energy from the microwave source. Various compromises are inevitable. So one can define some efficiency of the antenna system. In cases that reflector size is a problem this is important. Otherwise one can increase A to get the desired fields on the target, and thereby compensate for the non-ideal efficiency.

Given an optimum frequency around a GHz (or perhaps somewhat higher if ionospheric conditions are important) one can maximize the source power. For a given power one can maximize the antenna performance. One can even increase the antenna aperture for a given source power to further increase the target response.

As the foregoing discussion indicates there are various possible applications for some version of the phaser. Each scenario may lead to different optimizations. In any event significant advances seem quite feasible.

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