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Some Recent Advances in Microwaves – A Review

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ABSTRACT

Some recent advances in microwaves such as gyrotron, gyro-TWT, IMPATT, radio camera MIC, etc, which find applications in defence have been reviewed. Our claim is to brevity, not to profundity in originality.

1. INTRODUCTION

The aim of the present review will be to document briefly the significant progress achieved in recent years, heralding an era rich in engineering discovery and innovations in the area of microwave technology which now encompasses millimetre and submillimetre waves.

Prior to 1965, most of the microwave equipments incorporated waveguides, resonators and tubes which were an outgrowth of the principles well-established during legendary Maxwellian era and then followed in quick succession, solid-state devices such as tunnel diodes, varactors, switching diodes and stripline circuitry.

After 1965, expanding level of activity and cross-fertilisation of ideas spearheaded by new material development and semiconductor ingenuity made a break through in the development of microwave transistors, transferred electron diodes, avalanche diodes as power sources, schottky-barrier mixer diodes, PIN switching devices in control applications, fin-line devices followed by the developments during 1981-85, viz. microwave FET's, IMPATT diodes, integrated circuits fabricated on gallium arsenide (*GaAs*) and related compounds, the establishment of printed-circuit technology and more recently the conception of monolithic microwave integrated circuits (MMIC).

Developments of solid-state generators threatened to render microwave tubes obsolete. But the recent achievement in frequency stability and spectral purity and

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improved performance of microwave electronic devices proved adequate to serve the power needs of modern radar. Evolution of gyrotrons[1], free-electron laser (FEL)[2], using quantum-mechanical concepts provide useful needs of higher power defence weapons.

In the fields of electromagnetics and radar, high resolution microwave imaging is an important development. Microwave imaging is used for target classification, such as counting of targets, observation of their deployment and to distinguish between types of targets.

The invention of microwave sources[1] of astronomical power, the attempt to achieve invisibility[3] by changing the electromagnetic characteristics of targets provide fascinating and challenging fields of fruitful research.

It is almost impossible to keep pace with knowledge accumulating since last two decades at such an incredible fast rate, culminating in new physical concepts which soon fade into obsolescence and generate newer ideas and their utilisation in fabricating new types of microwave and millimetre wave (MMW) devices which find applications in various types of defence systems. Hence further discussions will be concentrated on only a few chosen topics.

2. GIGAWATT MICROWAVE POWER GENERATORS

High power megawatt microwave generators including classical devices such as klystron, magnetron, travelling wave tube (TWT) and backward wave oscillators (BWO) are well-established. Some typical examples are mentioned in Table 1.

Recent resurgence of activity to produce ultra-high power (of the order of gigawatts) at microwave frequencies has led to the exploitation of intense relativistic electron beam cyclotron instability. For instance, 10 MW X-band power has been generated using beam power of the order of 10^9 to 10^{10} W and electron energy 0.5 MeV, whereas, using beam power in the range of 10^{10} to 10^{12} W, and electron energy of 3 MeV X-band microwave power >> 1 GW was obtained at a single shot. The intense relativistic electron beam is produced with the help of a multimegavolt-electron accelerator[4]. The advent of vircator (virtual-cathode oscillator), gyrotron, FEL and beam-plasma devices have added to the list of high power microwave generators.

Table 1 State-of-the-art (1980) of microwave generators

Type	Peak power pulsed (MW)	Power output CW (av)	Efficiency (η) (%)	Frequency (f) (GHz)
2-cavity klystron	30	500 (kW)	40	10
Klystron used in 2-mile linear accelerator (Stanford)	24		36	2.856
Travelling wave magnetron	40	100–300 (W)	40–70	10

Different generators work in different frequency ranges giving different output power[5]. For instance, vircators work in the range of 1 to 20 GHz with power output ~ 10^4 to 10^3 MW and relatively broad-band width. Gyrotrons operate at MMW wavelengths having narrow bandwidths and yielding continuous wave (CW) power ~ 100 MW and in pulsed mode a power ~ 7 GW; FEL work in the GHz range producing peak power of more than 1 GW, whereas, beam-plasma devices which have the potential as broad-band (1 to 100 GHz) sources have produced peak power ~ 100 MW with pulse length ≃ 100 ns.

These high power microwave sources can be used for effective counter measures, jamming of communication signals and damaging electronic systems which use low power MOS logic chips, semiconductor components, etc. The principles of some of the available high power sources are briefly discussed in the following sections.

2.1 Free-Electron Laser

Free-electron generators of coherent radiation[6] are of profound interest because of their potential for high power radiation with high efficiency and wide tunability from the millimetre to the x-ray region by varying electron energy. FEL radiation is generated by passage of high energy relativistic beam through a spatially varying magnetic field which causes the electron beam to 'wiggle' and hence to radiate, provided (a) energy and momentum are conserved from the initial to the final state, and (b) the dispersion relationships are satisfied. The physical mechanism of FEL's is stimulated backscattering of a low frequency pump-wave (which takes the form of a 'wiggler' field) from a relativistic electron beam. Considering a completely non-neutralised relativistic electron beam moving in the z-direction in a wiggler field and the scattered fields composed of electromagnetic as well as electrostatic waves and using Vlasov-Maxwell perturbation analysis, the following dispersion relations[2] are obtained,

$$D(\omega, k_{\pm})\, \widetilde{A}_{\pm}(z) = 0$$

$$\text{and} \quad [1 + \chi(\omega, k)\, \widetilde{\phi}(z) = 0 \qquad (1)$$

where the electron susceptibility

$$\chi(\omega, k) = \frac{\omega_b^2}{k} \int \frac{m_0 \partial g_0 / \partial u \, du}{\omega - v_z k}$$

$$\text{and} \quad D(\omega, k_{\pm}) = \omega^2 - c^2 k_{\pm}^2 - \omega_b^2 \int g_0/\gamma \, du \qquad (2)$$

$k_0 = 2\pi/l$, where l is period of the static field.

$= \sqrt{(1+p^2)/m_0^2c^2}$ is the relativity factor, where m_0 = rest mass of electron, and $\vec{p}$ = momentum = $\gamma m_0 \vec{v}$; where $\vec{v}$ is the electron velocity and

$$A_{\pm}(z,t) = \widetilde{A}_{\pm}(z)\, \hat{e}_{\pm} \exp(-i\omega t) + \text{complex conjugate (cc)}$$

$$\phi(z,t) = \frac{1}{2}\widetilde{\phi}(z) \exp(-i\omega t) + \text{cc} \qquad (3)$$

are the vector and scalar potentials respectively and u denotes the magnitude of the total momentum. $g_0(u)$ is related to the equilibrium distribution function.

$$\begin{aligned} \omega_b &= (4\pi |e|^2 n_0 m_0)^{1/2} \text{ is the beam plasma frequency,} \\ v_z &= u_z/(m_0 \gamma) \\ \tilde{A}_{\pm}(z) &= \tilde{A}_{\perp} \exp(ik_{+}z) \\ \tilde{\phi}(z) &= \tilde{\phi}(0) \exp(ikz) \end{aligned} \tag{4}$$

where $k_{\pm}$ and k are real constants and n_0 is the ambient beam density far to the left of the interaction region. Table 2 shows some recent typical values of power generated at MMW by FELs.

Table 2. Typical values of power generated by FELs

Wavelength (mm)	Power (P) (GW)	η (%)	Reference
8.6	1	34	7
8.6	17	27	8

Schwinger's[9] work which explained the production of synchrotron radiation by free electrons, Motz's[10] proposal and realisation of a device known as 'undulator' to produce radiation by passing a high energy electron beam through a wiggler magnetic field, Smith and Purcell's[11] device led to the introduction of gyrotron in which the transverse orbital motion of bunched electrons in the presence of a magnetic field is used to produce MMW radiation. It may be operated at high power levels with a fairly high efficiency but is severely limited in tuning range because of the need to couple to waveguide modes.

2.2 Gyrotron

The entire sequential development of electron tubes starting from electron emission to various types of LF, HF and UHF tubes, their replacement in the higher frequency region due to limitations of transit time effects, leading to the genesis of microwave tubes, followed by conventional classical electron devices based on stimulated transition by free electrons and quantum devices using electrons oscillating in atom provided a chain of thought-provoking concepts proposed by an array of scientists working with fecund motivation ultimately resulted in the evolution of gyrotron and other gyro-devices, such as gyro-TWT and gyro-TWTA[12,13].

The physical mechanism of operation of a gyrotron can be explained as follows. Electron motion in a uniform magnetic field with flux density $\vec{B}$ corresponding to a rotation of its velocity vector $\vec{v}$ (relativistic or non-relativistic) with angular velocity

$\vec{\Omega}\ (= -c^2/U \times e\vec{B})$ is described

$$\frac{d\vec{v}}{dt} = \vec{\Omega} \times \vec{v} \tag{5}$$

where the energy $U = \gamma m_0 c^2$, where $\gamma = (1-v^2/c^2)^{-1/2}$. The magnitude $|\vec{\Omega}|$ is known as gyrofrequency. But under subrelativistic condition ($v^2/c^2 << 1$), $\vec{\Omega}$ reduces to $\vec{\Omega}_0$ ($= e\vec{B}/m_0$) which is known as cyclotron frequency. Hence gyrofrequency is a relativistic term, whereas cyclotron frequency is a non-relativistic term.

The trajectory Eqn. (5) can be written as

$$\frac{d\vec{v}}{dt} = \vec{\Omega} \times \vec{v}_{\perp} \qquad (6)$$

since $(\vec{v}_{\perp} + \vec{v}_{\parallel}) = \vec{v}$ and $d\vec{v}_{\parallel}/dt = 0$, $\vec{v}_{\parallel}$ being parallel to $\vec{B}$. Eqn. (6) yields a trajectory of cylindrical helix of radius R ($=p \sin a/eB$) where $\vec{p} = m\vec{v}$ and $a = (\sin^{-1} v_{\perp}/v)$ denotes the pitch angle. In Cartesian frame the trajectory is helichoidal. This is an important requirement of gyrotron. In crossed electric and magnetic fields electrons describe a trochoidal trajectory. The question then arises which of the two trajectories is more suitable for gyrotron. This can be answered from a study of the condition of cyclotron resonance given by

$$\Omega = \omega - k_{\parallel} v_0 \qquad (7)$$

provided the velocity is single-valued. $k_{\parallel}$ denotes the parallel component of the wave vector $\vec{k}$ and $\vec{v}_0$ is the translational velocity. If the velocity is multi-valued as is usually the case, the condition of resonance (Eqn. 7) is not satisfied. In helichoidal beam, longitudinal velocity scatter is inevitable, whereas in a trochoidal beam, the translational velocity ($= cE/H$) is single-valued for all electrons in a stream. From this stand point, trochoidal beam is preferable. But if an ensemble of electrons interact with an electromagnetic wave propagating at right angle to $\vec{B}$, thus making the term $k_{\parallel} v_0$ vanish, then helichoidal beam can be profitably used to yield more power and efficiency. This is achieved in gyrotron by using the medium of interaction, a waveguide near cut-off. This is an essential condition for gyrotron.

An ensemble of electrons gyrating in an external magnetic field get bunched azimuthally in their gyration orbit due to the dependence of $\vec{\Omega}$ on the relativistic mass m in the presence of resonance. This phenomenon known as cyclotron maser instability[14] due to wave-electron interaction has been employed to develop electron cyclotron maser (ECM) or gyrotron. In contrast, wave-electron interaction in the absence of resonance gives rise to a different type of electromagnetic instability known as 'Weibel' instability produced due to anisotropic distribution of the velocity of electrons. Weibel instability gives rise to axial bunching of electrons due to the Lorentz force $\vec{v}_{\perp} \times \vec{B}_1$, where $\vec{B}_1$ denotes the wave magnetic field. A comparative study of the two types of bunching shows that the azimuthal bunching prevails if

$$\omega\Omega_e/\gamma_0 k_z^2 c^2 > 1 \qquad (8)$$

whereas if

$$\omega\Omega_e/\gamma_0 k_z^2 c^2 < 1 \qquad (9)$$

axial bunching prevails, where $\Omega_e = eB_0/m_c$ and k_z denotes the z-component of the wave vector. Power levels[15] for gyrotron over a range of frequencies are given in Table 3.

Table 3. Peak power levels of gyrotron

λ (cm)	Peak power (MW)	Accelerating voltage (MV)
	900	3.3
	350	2.6
0.4	2	0.6

2.2.1 *Gyro-Travelling Wave Tube Amplifier (TWTA)*

The principle of operation of a TWTA is based on the interaction between a fast-wave propagating mode in a waveguide with the fast cyclotron wave of the electron beam. The power gain[12] is given by

$$G(\text{db}) = -10\log_{10} 9 + 8.68\,\Gamma L \tag{10}$$

where the loss is represented by $-10\log_{10}9$ and the spatial growth rate near the point of grazing incidence is denoted by Γ and L is the length of the amplifying region.

3. SOLID-STATE MICROWAVE GENERATORS : IMPATT DIODES

The maturing of improved semiconductor technology helped the growth of solid-state coherent microwave generators such as Gunn diode and in particular, IMPATT diodes. Microwave oscillations in III-V semiconductors such as a *n*-type *GaAs* was observed[15] when it was subjected to a constant electric field exceeding a few kV/cm. Before this effect known as Gunn effect was observed, it was predicted[16,17] that a negative differential resistivity could result from the progressive transfer of hot electrons from a high mobility valley in the conduction band to a low mobility valley at higher energy. Theoretical analysis[18] showed that the electron transfer mechanism and the subsequent break up of the sample into regions of high and low field could account for the Gunn effect. Some typical results[19] obtained using Gunn oscillators are given below in Table 4.

Table 4. Power and frequency of Gunn oscillators (LSA mode)

f (GHz)	*P* (watts)	*η* (%)
Operation pulse		
44–51	0.5	3
84	0.05	4
Operation CW		
44–51	0.02	0.7
84–88	0.02	2

The proposal of Read[20] was modified[21] to construct an avalanche transit time oscillator by employing the depletion region of a simple silicon *pn*-junction which was further modified[22] taking into account avalanche breakdown and transit time effect to develop[23] impact avalanche transit time (IMPATT) oscillators in *Ge* and *GaAs*. The state-of-the-art regarding *GaAs* and *Si* IMPATT is given in Table 5 which shows that *GaAs* diodes are effective at microwave frequencies, whereas *Si* diodes are effective at MMW frequencies.

Table 5. State-of-the-art (1967) of IMPATT : *GaAs* and *Si*

f (GHz)	η (%)	Material	Type of junction	Operation
13.6				
50				

For MMW operation the single-drift (p^+-n-n^+) and double-drift (p^+-p-n-n^+) types of complex diode structure[25] are very effective. The double drift type is equivalent to two single-drift type connected in series, thus yielding much higher output power than the (p^+-n-n^+) type. The ultimate power is limited by the realisable circuit impedance, in particular, at higher frequencies. Since the double-drift type yields higher impedance for a given junction area, power output of about four times that of the single-drift type can be realised. Various types of oscillator/amplifier circuits[25] such as reduced height, hat resonator and coaxial waveguide cavity have been developed. It is found that output power (P) as a function of frequency (f) varies from 2 watts at 40 GHz to several milliwatts at 230 GHz. It is also found that at $f <$ 100 GHz, pf = constant indicating that P_{out} is determined by thermal limitation, whereas at $f >$ 100 GHz, pf^2 = constant indicating that P_{out} is determined by circuit impedance. It is also found that *Si*-IMPATT diodes is currently (1979) reaching the 300 GHz range.

4. MICROWAVE INTEGRATED CIRCUITS (MICs)

The discovery of transistor before 1950, its practical applications in electronic circuitry, emergence of solid-state devices, such as tunnel diodes, varactors PIN diodes after 1965, major break through in the development of microwave transistors, avalanche diodes, etc., leading to the introduction of semiconducting chips with a volume 82 to 812×10^{-7} cm^3 and microstrip packaging technology which provided great scope for radar applications resulted in the outgrowth of MICs[26,27]. This introduced a new era of miniaturisation which provided improved reproducibility, higher reliability and often better performance of microwave devices which could be readily incorporated in defence oriented systems[28].

MICs are, in general, of two forms incorporating either distributed[29] or lumped[30] or a combination of both types known as hybrid[31] MICs. Microwave circuit integration technique is primarily based on the use of planar transmission line, for example, microstrip as the transmission medium[32-37].

MIC technology possessess the advantage of combining multi-circuit functions without any interconnecting wires, which enables production of compact integrated modules with highly reliable performance. There are other transmission lines, viz. slot line[38], suspended and inverted microstrip[39] and also other types[40].

As the techniques and applications of MICs have matured, a significant innovation occurred by the introduction of monolithic (MMIC) technology. In the monolithic circuit, active devices are grown *in situ* or in a semiconducting substrate and passive circuitry is either deposited on the substrate or grown in it. Recently, using MMIC configuration balun[41], BPSK modulator[42] and Ku-band phase-locked oscillator[43] have been developed. Gallium arsenide microwave and millimetre wave devices and MMICs which find application in radar and phased array systems have been recently developed[44]. The fabrication technique of MMICs involves device technology using epitaxial or ion implantation, multi-level metallisation and a composite process involving photo-lithography and electron beam lithography. The fabrication of MICs uses either monolithic or hybrid technology using thin film[45] or thick film[46]. The latter is more prevalent due to its advantages in terms of simplicity of fabrication.

4.1 Fin Lines

The extension of microstrip as a transmission medium to mm wavelengths suffers from the disadvantages of critical tolerance and very narrow conductor strips that are not compatible with hybrid devices. To overcome this difficulty, fin line techniques as originally used[47,48] was modified[49] and introduced as a transmission line for MMW ICs so as to provide isolation from the waveguide circuit.

Fin line medium has been combined with other planar waveguiding structures like microstrip and coplanar line to form quite versatile mixed waveguide ICs mounted in the E-plane of a metal waveguide housing[50]. There are four types of fin line, namely, unilateral, bilateral, isolated and antipodal. Recently, all important circuit components such as, filters, directional couplers, PIN diode attenuators, switches, mixers, modulators, circulators and subsystems such as oscillators, etc, have been realised[51,52].

5. MICROWAVE IMAGING : RADIO CAMERA

Radio camera epitomises the great change that has recently come over the character of technological frontiers and plays an important role in the field of radar detection of targets and extraction of information about their identities by using the principle of high resolution microwave imaging[53]. It essentially consists of a pulsed transmitter for illuminating the target, a self-adaptive random phased array followed by a microwave receiver which produces the hologram from which the intensity and phase information of the target radiation, and hence identity is derived. A radio camera is thus an outgrowth of holography.

The principle of microwave imaging can be stated with the aid of the following integral equation

$$\tilde{s}(u) = \int i(x)\,[s(u')\exp(jkxu')du']\exp(-jkxu)dx \tag{11}$$

By using the convolution properties of Fourier tranform, Eqn. 1) is transformed to

$$\tilde{s}(u) = f(u) * s(u) \quad 12$$

where the source (or the scene to be imaged) and the image functions are denoted by s and $\tilde{s}$ respectively, when the radiation field due to the source is measured by a line aperture of extent L with aperture weighing i. The source is assumed to be in the far field of the aperture. The radiation or diffraction pattern is represented by $f(u)$.

Achievement of the antenna size required for successful microwave imaging demands a distributed antenna such as a phased array. Significant contributions towards the improvement of performance of phased array have recently been made by Das *et al*[54,55].

5.1 Optical Holography

Holography initiated by Gabor[56] and improved by Leith and Upatnieke[57] consists of recording interference between radiation field from an object to be imaged and a reference field, thus producing hologram which contains information about the amplitude and phase of the object wave field. The final step in the process is the reconstruction of the identity of the object.

5.2 Microwave Holography

The basic principle of wave front reconstruction in both optical and microwave holography is the same. But in the latter case, we need large antenna aperture for sensing the radiation emanated from the object whose high resolution image is to be formed. Such a large aperture antenna can be formed by using 10^8 to 10^{10} elements. If the elements are equispaced, the spacing between adjacent elements is $\leq \lambda/2$ in order to avoid grating lobes. In order to obtain a resultant coherent output from all elements, a bank of phase shifters are used. The required number of elements can be reduced to 10^3 to 10^4 provided the distribution of elements is random[58] in order to avoid grating lobes. The reduction in the number of antenna elements and phase shifters makes microwave imaging more practical.

But due to the following drawbacks inherently associated with a large aperture array, namely, (a) lack of mechanical stability of antenna elements, (b) variation of electromagnetic coupling between elements and local environment, and (c) variation of driving point impedance across the array elements due to differential weather, etc., random phase variation in the output from the elements is inevitable. Hence to obtain coherent output it is imperative that the antenna array must be self-adaptive[59].

5.3 Adaptive Microwave Holography

High resolution microwave imaging[60,61] involves several processes, such as (a) sampling of the object radiation by each element of an adaptive antenna system, (b) heterodyning the signal to a lower intermediate frequency (IF) with the aid of a properly phased local oscillator so as to preserve the amplitude and phase relations of the object radiation field, (c) demodulating coherently the signal in quadrature demodulators, and (d) sampling and storing of the resolved components of the IF wave. The data thus stored constitutes the microwave hologram.

6. RADAR CROSS-SECTION - METHOD OF REDUCTION

The development of radar – an outgrowth of electronics and electromagnetics – has been stimulated primarily by military needs for surveillance, navigation and weapon control. How far a radar can detect or track an object depends on its transmitter power, antenna size, receiver sensitivity, environmental conditions and principally the radar cross-section (RCS) of the target. The fundamental relationship between these parameters and received power P_R is given by the radar range equation

$$P_R = P_T G^2 \lambda^2 \sigma / (4\pi)^3 R^4 \tag{13}$$

which when solved[62] for the maximum range (R_{max}) in terms of the ratio of transmitted power (P_T) to a minimum detectable power (P_{min}) yields

$$R_{max} = (P_T/P_{min})^{1/4} \, [A_e \; G\sigma/4\pi^2]^{1/4} \tag{14}$$

where $A_e = G\lambda^2/4$, G being the gain of the transmitting-receiving antenna. The scattering corss-section of the target is denoted by σ.

Hence, in order to have detection distance halved, RCS must be reduced by a factor of 16. If radar echo of an aircraft flying head-on is reduced from 5 to 0.5 sqm, the detection range is reduced by 44 per cent, all other parameters remaining the same.

Two important cases, namely, (a) enhancement of R_{max}, and (b) reduction of R_{max} need consideration according to operational necessity such as detection of a flying object like aircraft, missile, etc., or camouflaging a target. The first requires increased P_T, G or σ and reduced A_{min} which involves the consideration of signal-to-noise ratio (SNR) of the system. The second case can be achieved by reducing σ. We will discuss the methods to reduce σ, so as to achieve, if possible, the invisibility of either a moving or stationary object.

One of the methods used during 1940s is to coat the target with radar absorbent material. This led to intensive research in radar scattering which was partially successful in evolving low observable techniques which made targets less detectable to radar but not invisible.

Absorbers, in general, are of two types namely, (a) interference absorbers, in which reflections occurring at the front surface of the absorber are cancelled by destructive interference with the wave that enters the layer and subsequently emerges, and (b) antireflection coatings, in which the absorber material is so designed that no reflection takes place at the front surface and the attenuation in the layer extinguishes the entering waves.

If a plane wave is incident on an infinitely extended sheet of material, having physical properties $\tilde{\varepsilon}$ and $\tilde{\mu}$, where the tilde (~) refers to complex values, the amplitude reflection coefficient ψ is obtained by solving Maxwell's equations and applying appropriate boundary conditions as[63]

$$\psi = \left[\sqrt{(\tilde{\varepsilon}/\tilde{\mu})} - 1\right] \Big/ \left[\sqrt{(\tilde{\varepsilon}/\tilde{\mu})} + 1\right] \qquad (15)$$

$\psi \rightarrow 0$ as $\tilde{\varepsilon} \rightarrow \tilde{\mu}$ which is possible provided *Im* $(\tilde{\varepsilon})$ is large.

This is the case favourable to the invisibility of a target to radar. This type of absorber belongs to the second type of absorbers. ψ can be written in terms of refractive index n and absorption index κ and $\tilde{\mu}$ as

$$\psi = (n + i\kappa - \tilde{\mu})/(n + i\kappa + \tilde{\mu}) \qquad (16)$$

The calculation of the resultant reflection coefficient can be made in the case of interference absorber by adding the emergent rays with the wave reflected from the interface between the front surface of the material and air. If d denotes the thickness of the coating, the minimum reflection occurs when

$$\sin(4\pi nd/\lambda) = 0 \qquad (17)$$

or

$$\cos(4\pi nd/\lambda) = -1 \qquad (18)$$

which lead to the condition of cancellation of the resultant wave as

$$(4\pi nd)/\lambda = (2p - 1)\pi,\ p = 0,1,2$$

i.e.

$$d = (2p - 1)\ \lambda/4n \qquad (19)$$

i.e., the phase change must be π and the thickness of the coating must be odd multiple of quarter λ. Hence, the condition that the emergent wave produces complete cancellation is

$$(4\pi nd)/\lambda = \ln \psi^{-1} \approx 2\mu/n \qquad (20)$$

which may be said to be the condition of invisibility.

Ferrite-ceramic materials, such as iron oxides to which small amounts of metals like cobalt and nickel have been added are well-known wide band width absorbers below 1 GHz. Ferrite-based paints are also used from 3.5 to 13 GHz and also rubber sheets to absorb upto 20 GHz.

The use of traditional materials for coating increases the volume and weight of the target. But the substitution of composites or plastics for metal will reduce weight. For example, carbon-epoxy is being currently used for some aircraft wing skin and is about as strong and stiff as aluminium alloys and yet about 40 per cent lighter[3].

The other known method to reduce RCS is to use honey-combed sections in key areas of the target to trap incoming waves[3].

7. CONCLUSIONS

On the basis of the information presented above, collected from available published literature, it can be concluded that further basic work needs to be done in various fields. The following comments may be pertinent.

(i) A critical future need is to develop low-noise solidstate sources capable of tens of milliwatts for operating at 100 GHz and higher frequencies.

(ii) Though the range of applications of the new fin line technologies continues to grow in various fields including radar and communication equipments, it is not known what are the limiting factors needed concerning frequencies higher than 170 GHz and higher power transmissions due to the printing accuracy of the order of $\pm\mu$m.

(iii) In microwave regions where $\lambda <<$ target size, shape is all important. But reducing RCS in one aspect often enhances it at another. So, the target's most important profile must be selected.

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