DIELECTRICALLY-LOADED WAVEGUIDE AS A SHORT PERIOD SUPERCONDUCTING MICROWAVE UNDULATOR*

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Abstract

The HEM_{12} mode in a cylindrical, dielectrically-loaded waveguide (WG) provides E and H fields on the central axis that are significantly higher than the fields on the conducting walls. This waveguide structure could be designed to operate near the cutoff frequency of the HEM_{12} mode where the wavelength and phase velocity vary significantly to enable tuning of the equivalent undulator wavelength by changing the frequency. A typical frequency range would be from 18 – 24 GHz. It would be possible to generate high-energy, 45 to 65 keV, x-rays on the fundamental mode which are tunable by changing the source frequency while maintaining a constant equivalent undulator field strength on axis field of 0.5-T. The x-ray brightness of the microwave undulator would be up to 4 to 7 times higher than what is available with the APS 1.8 cm period Superconducting Wire Undulator.

INTRODUCTION

The benefits of a tunable high-energy x-ray source at the Advanced Photon Source (APS) were summarized in a workshop that was held at the APS in August of 2004 [1]. Presently, x-rays at energies greater than 25-keV are generated on the higher harmonics of permanent magnet undulators, or more recently on the APS superconducting wire undulators (SWU) [2]. Ultimately, the magnetic undulator is limited in generating x-rays on the fundamental mode to 20 to 30-keV because the undulator periods required are near, or under, 1-centimeter, which results in restrictively small vacuum apertures on the order of a fraction of a centimeter to achieve a reasonable deflecting field on axis.

If a superconducting microwave undulator can be realized, it would provide the advantage of larger vacuum apertures up to 5 cm, x-ray generation on the fundamental mode of the undulator, and a constant brightness.

Microwave undulators were first proposed by Shitake at KEK [3] and Batchelor at BNL [4] in 1983 using rectangular waveguides. Recent studies have been directed towards open-mode structures, over-moded waveguides (WGs), ridge WGs, square WGs, corrugated WGs, and elliptical WGs [5,6,7,8]. The SLAC group have built a room temperature microwave undulator that operates in pulsed mode with tens of MW of input power [6]. The device generates a 0.65-T equivalent undulator field.

A short model of a superconducting microwave undulator using an elliptical WG operating at 6-GHz was built and tested in a cryostat at Frascatti [8]. It achieved an equivalent undulator field of 330-gauss with a 10-watt heat loss. The field was limited by the size of the amplifier.

The challenge of these geometries is finding one that achieves high fields on axis with minimal losses on the conducting walls to minimize power requirements from the source. This is especially true if continuous wave (CW) operation is desired at superconducting temperatures. Since the loss factor of sapphire is very low at cryogenic temperatures, it is possible to consider using it in a dielectrically-loaded WG as a superconducting microwave undulator.

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HEM_{12} MODE

The HEM_{12} mode in the dielectrically-loaded WG is the sum of a TE and TM mode for which the velocity of propagation is identical for each mode and for which the fields are matched at the dielectric boundary. The WG structure is a cylindrically symmetric tube with an inner radius of the dielectric, a, and the outer radius, b. The conducting boundary of the WG structure is at radius b. The electric and magnetic fields in the vacuum region of the WG are listed in Eq. 1 through 6.

$$E_z = E_0\, J_1(x_{np}\,\rho)\cos(\phi) \qquad [1]$$

$$H_\rho = -j\,\{E_0\,\omega\,\varepsilon_0\,J_1(x_{np}\,\rho)\sin(\phi)\}\,/\,(h^2\,\rho) \qquad [2]$$

$$H_\phi = -j\,\{E_0\,\omega\,\varepsilon_0\,J_1'(x_{np}\,\rho)\cos(\phi)\}\,/\,h \qquad [3]$$

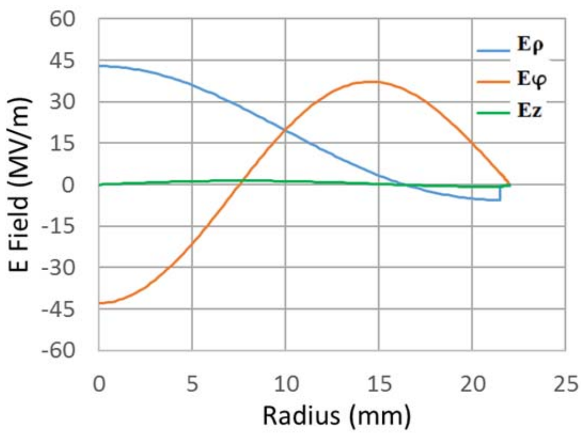
$$E_\rho = (\beta\, H_\phi)\,/\,(\omega\,\varepsilon_0) \qquad [4]$$

$$E_\phi = (-\beta\, H_\rho)/\,(\omega\,\varepsilon_0) \qquad [5]$$

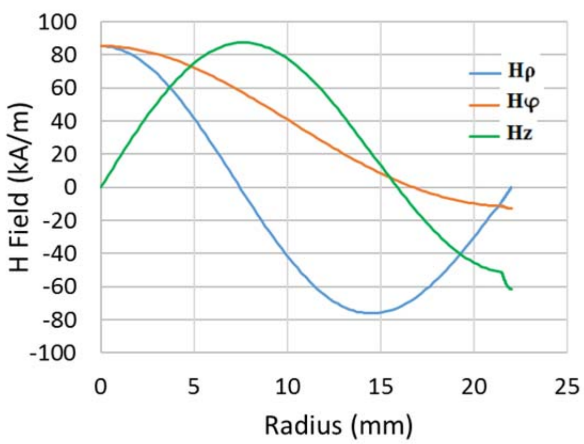
$$\beta = [\omega^2\,\mu_0\,\varepsilon_0 - h^2]^{1/2} \qquad [6]$$

where E_0 is a constant, $\omega = 2\pi f$, ε_0 is the free space permittivity, $J_1(x_{np}\,\rho)$ is the Bessel function of order 1, $J_1'(x_{np}\,\rho)$ is the derivative of $J_1(x_{np}\,\rho)$ with respect to its argument, $(x_{np}\,\rho)$, x_{np} is the zero of the Bessel function, and $h = x_{np} / a$.

Figure 1 shows the E & H fields for an example structure where the radius a = 2.15-cm, the radius b = 2.2-cm, and the dielectric is sapphire with a permittivity 9.9. The frequency of the propagating wave is 18-GHz. The E_z and H_z fields are zero at the origin. The magnitudes of the H_ϕ and H_ρ add on the origin, as do the magnitudes of the E_φ and E_ρ field components to generate strong H_y and E_x fields in the transverse Cartesian plane. Fig. 2 is a Microwave Studio [9] computer generated plot of the transverse H-field for the same HEM_{12} mode at 18-GHz in Fig.1.



(a)



(b)

Figure 1: Field components for a HEM_{12} mode along radial direction: (a) Electric Field and (b) Magnetic intensity.

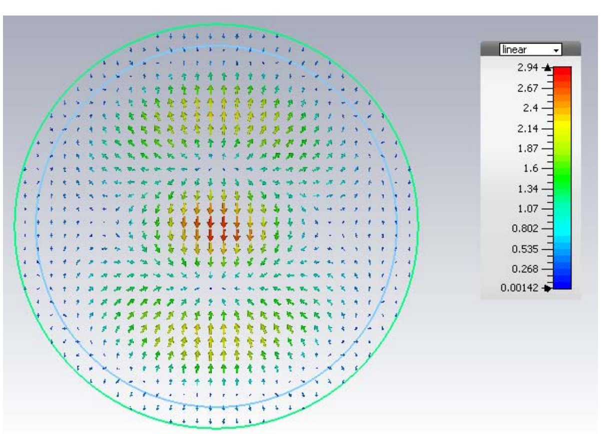


Figure 2: H field plot for HEM_{12} mode in amps/m.

UNDULATOR BEHAVIOR OF HEM_{12} MODE

The force, F_d, on a particle with a charge, q, traveling in a direction towards the oncoming wave sees a transverse deflecting force, shown in Eq. 7.

$$F_d = q\,(E_x + v\,\mu_0\,H_y) \qquad [7]$$

where v is the particle velocity and μ_0 is the permeability of free space.

The cutoff frequency, f_c, the frequency below which propagation is not possible, for a given WG mode is determined by its transverse geometry. The phase velocity of the EM wave, v_p, at the operating frequency, f, is related to f_c and the speed of light, c, as shown in Eq. 8.

$$v_p = c\,/[1 - (f_c/f)^2]^{1/2} \qquad [8]$$

The equivalent undulator wavelength, λ_u, is given in Eq. 9 [3,4], where λ_g, is the wavelength of the wave in the WG. It is clear from Eqns, 8 & 9 that the equivalent undulator wavelength, λ_u, can be changed significantly by changing the operating frequency.

$$\lambda_u = \lambda_g/(1 + v_p/c) \qquad [9]$$

The equivalent undulator field can be held constant by adjusting the source power. Therefore, x-rays can be generated on the first harmonic of the undulator. The on axis brightness (ph/s/mrad^2/mm^2/0.1%bw) of the example WG design shown in Figs. 1 & 2, where the equivalent undulator field is maintained at 0.5-T and the frequency is changed over the range of 18-GHz to 24.5-GHz, is shown in Fig. 3. Comparison between the existing SWU device on the APS (SCU 1.8 cm, 1.08 m long), possible future SWUs (SCU: 1.8 cm, 1.08 m & SCU: 1.6 cm, 1.8 m), and MSUs of lengths, 1.0, 1.08, 1.5, 1.8 m (shown as rf-SCU) are shown in Fig. 3 [10].

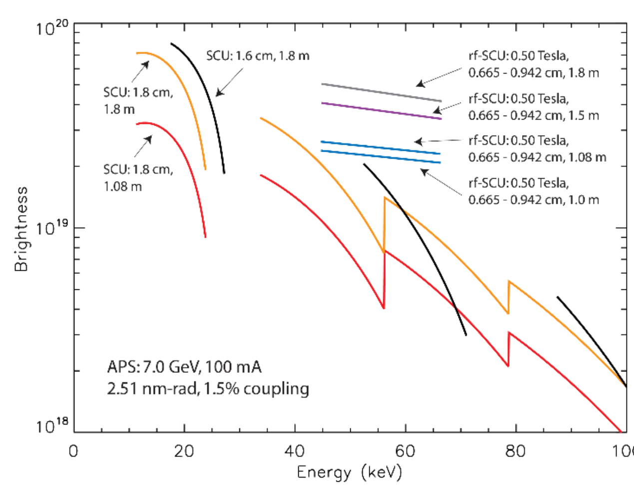


Figure 3: X-ray brightness, ph/s/mrad^2/mm^2/0.1%bw, as a function of x-ray energy for the HEM_{12} example WG over the frequency range of 18-GHz to 24.5 GHz and for various lengths. Comparison plots are also made for the existing APS SWU (1.8cm, 1.08 m) and possible future SWUs.

SUPERCONDUCTING OPERATION

It is possible to consider superconducting operation with sapphire as the dielectric since the loss tangent of sapphire at 2-4 K can be as low as $2x10^{-9}$ [11]. And, since the dielectric walls are radially thin, the losses due to the dielectric are considerably smaller than the wall losses. The magnetic fields on the superconducting outer wall are only about 0.07-T with an equivalent undulator field held at 0.5-T on-axis. The calculated wall losses vary from 170-w to 270-w over the frequency range of 18 to 24.5-GHz. The surface resistances were calculated using the standard formula with the operating temperature at 1.8-K [12].

These power levels are still somewhat too high for CW operation unless the surface resistance can be lowered further than what is predicted by the standard formula. If the reductions in surface resistance achieved by Grassellino [13] can be achieved on the dielectrically-loaded WG, then CW operation could well be possible. A future possibility for CW operation could be MgB_2, which has a critical temperature of about 40 K [14]. Theoretically, the higher critical temperature could result in a sufficiently low surface resistance for CW operation. If lower surface resistances are not possible, then long pulse operation, as is being implemented on some Free Electron Facilities, would appear possible.

FABRICATION

Smooth, hollow, thin-wall sapphire tubes for infrared waveguides with outer diameters between 0.6 to 1.5-mm, wall thicknesses between 75 to 230-microns, and total lengths up to 1.25-m long have been tested for transmission losses by Harrington and Gregory [15]. Commercial hollow tubes are available up to a few cm in diameter and 1.65-m in length [16]. Therefore, the technology of manufacturing the sapphire dielectric appears feasible. Ideally, it would be best if the sapphire dielectric could be grown unto the inside diameter of a hollow Nb tube with high quality superconducting properties. Otherwise, the Nb tube would either slide over the sapphire tube or be sputtered unto the sapphire liner. The former approach could result in a small vacuum gap between the dielectric tube and the Nb tube. This should be tolerable since the E fields are low on the outer diameter of the WG. The challenge of the sputtering technique is achieving low surface resistance on the dielectric and Nb conducting wall interface.

The cryogenic system design should not require anything more than a conventional cryostat design typical of existing superconducting systems.

MICROWAVE SYSTEM CHALLENGES

The microwave system for an MSU located in a synchrotron ring presents some challenges that would ultimately need to be addressed. To achieve continuously smooth x-ray energy tuning suggests the use of a resonant-ring where the power is returned from one end of the MSU WG to the other end with one or more return WGs. The circulating power would be fed back into the structure through the return WG. Power losses are supplied through multi-slot couplers in the return WG and designed to match the WG wavelength for the desired mode, thereby eliminating degenerate modes that are inherent in an over-moded WG. Low loss bends for coupling the dielectrically-loaded WG to the return WG would be designed over the frequency band as well as an additional mechanism for phase adjustment in the return WG which may be required.

Rack mounted power sources that have sufficient power with 10% tuning ranges are commercially available. At least two amplifiers would be used to get the full tuning range shown in Fig. 3 and to provide phase control.

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