Vol 18 No 6, June 2009
1674-1056/2009/18(06)/2445-07

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

7.8 GHz power generation device design using a rectangular dielectric-loaded waveguide*

Lu Zhi-Gang(路志刚)†, Gong Yu-Bin(宫玉彬), Wei Yan-Yu(魏彦玉),
Xu Jin(徐 进), Gao Peng(高 鹏), and Wang Wen-Xiang(王文祥)

School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, *China*

(Received 3 May 2008; revised manuscript received 20 October 2008)

In this paper, we present a design where a bunched relativistic electron beam traversing inside the rectangular dielectric-loaded (DL) waveguide is used as a high power microwave generation device. Two kinds of methods of calculating the electromagnetic (EM) field excited by a bunched beam are introduced, and in the second method the calculation of EM pulse length is discussed in detail. The desired operating mode is the LSM_{11} due to its strong interaction with the electron beam. For the designed 7.8 GHz operating frequency, with a 100 nC/bunch drive train of electron bunches separated by 0.769 ns, we find that high gradient (> 30 MV/m) and high power (> 160 MW) can be generated. An output coupler is also designed which is able to extract the generated power to standard waveguides with a 94% coupling efficiency.

Keywords: dielectric-loaded, rectangular waveguide, high power, relativistic electron beam
PACC: 5270G, 4110H

1. Introduction

Dielectric-loaded (DL) waveguide structures have been studied for many years.[1−3] Recently, for future high gradient microwave generation devices, there has been some interest in rectangular DL waveguides.[4] As shown in Fig.1, a rectangular DL waveguide is composed of a metallic rectangular waveguide (inner dimensions: $w \times 2b$) with two dielectric slabs (dimensions: $w \times (b - a)$), separately, at the top and the bottom of the waveguide. The dielectric reduces the phase speed of electromagnetic (EM) waves such that the EM waves can synchronize with charged particles for efficient interaction between them. The region between the two slabs provides a rectangular vacuum channel for the beam. The LSM_{11} mode is often chosen as the operating mode since it has the strongest interaction with an on-axis beam. By changing the height and the slab thickness of the waveguide, and the permittivity of the dielectric, the structure can be tuned so that the phase speed is set to be the particle speed at the desired frequency. In Fig.1, a particle bunch traveling through the waveguide is shown. The EM field excited behind the beam can be extracted from the structure by using an appropriate coupler. Compared with the circular DL

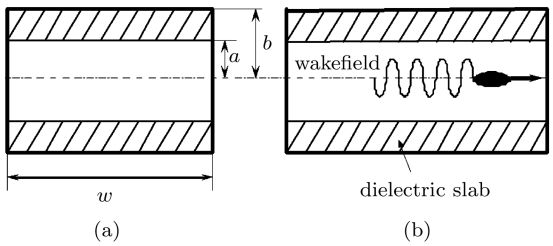


Fig.1. Transverse (a) and longitudinal (b) cross-sectional views of the rectangular DL waveguide with an electron bunch traversing inside the structure and EM fields exiting.

waveguide, this structure is attractive because of the following aspects:

(i) Tuning: the operating frequency of the rectangular waveguide can be easily adjusted by moving the metallic side walls inwards/outwards, if clearance is provided between each dielectric slab and the adjacent side wall;

(ii) Stored energy: at a certain frequency for a given gradient the rectangular waveguide can store more energy than a cylindrical one, thus beam loading can be reduced;

(iii) Focusing: in the beam channel, the EM field is not uniform transversely, so there exist transverse forces on a relativistic beam, which is able to provide a focusing force that acts on the beam, serving as a

*Project supported by the State Key Program of National Natural Science Foundation of China (Grant No 60532010).
†Corresponding author. E-mail: lzhgchnn@uestc.edu.cn

magnetic quadruple, while the beam is being accelerated or decelerated.

In the present paper, we report on the design for a 7.8 GHz power generation device using a rectangular DL waveguide, in which power generated by a drive beam, either a single bunch or a bunch train, is transmitted through an output coupler to standard waveguide. The remainder of the present paper is organized as follows. In Section 2 two methods to calculate the EM field excited by a bunched beam are introduced, and the calculation of EM pulse length is discussed in detail. In Section 3 the design of the rectangular DL waveguide and the design of an efficient wide-band output coupler are shown. Finally, the conclusions drawn from the present study are given in Section 4.

2. Theoretical calculation of EM field excited by electron beam

In this section, we will give two kinds of methods to calculate the EM field excited by a bunch relativistic electron beam. Meanwhile, using the second method we will deduce the calculating formula of EM pulse length.

2.1. Method I

This method is based on the field theory.

The EM field, which is excited by a bunched relativistic electron beam, can be expressed as a sum of an infinite series over all modes, where each term is a function only of the structural parameter (R/Q) for a corresponding mode,[5] with R being the shunt impedance per unit length and Q being the quality factor. The summation is an infinite series and it can be truncated by taking the integral over the finite bunch length of the drive beam. The longitudinal E-field amplitude, E_0, excited by a charged particle beam traveling on axis can be easily obtained as follows:[6]

$$E_{0i} = 2k_{li}q = \frac{q\omega_i}{2}\left(\frac{R}{Q}\right)_{(x_0,y_0)_i} \tag{1}$$

where the subscript i indicates the i^{th} mode; k_l is a normalized loss factor, ω is the angular frequency, $(R/Q)_{(x_0,y_0)}$ is calculated at the beam particle instantaneous position (x_0, y_0), and q is the electron charge. The mode selection for longitudinal E-field calculation is based on the relation between system response and signal excitation,[4] and in the present paper the LSM_{11} mode is selected. Adopt a Gaussian longitudinal beam shape (with bunch length σ_z and charge q), then the longitudinal E-field $E_z(z)$ at distance z behind the drive beam will be given by[4]

$$E_{\mathrm{z}}(z) = \frac{1}{\sqrt{2\pi}\cdot\sigma_{\mathrm{z}}}\int_{-\infty}^{z}\sum_{i=1}^{\infty}E_{0i}\cos[(\beta_{\mathrm{z}})_i(z-z')] \times\exp\left(-\frac{z'^2}{2\sigma_{\mathrm{z}}^2}\right)\mathrm{d}z', \tag{2}$$

where β_{z} is the longitudinal propagation constant of the i^{th} mode, and $\omega/\beta_{\mathrm{z}} = c$ on the assumption that the mode is synchronous with an ultra-relativistic beam.

2.2. Method II

For each mode in the structure, the longitudinal E-field amplitude E_0 and the stored energy per unit length U are related to each other through the normalized shunt impedance R/Q as follows:

$$\left[\frac{R}{Q}\right] = \frac{E_0^2}{\omega U}. \tag{3}$$

The R/Q of each mode can be calculated with standard EM codes such as CST Microwave Studio. The traveling wave power P_{w} is related to E_0 through

$$P_{\mathrm{w}} = \frac{E_0^2}{2\alpha_0 R}, \tag{4}$$

where $\alpha_0 = \omega/2Qv_{\mathrm{g}}$ is the field attenuation per unit length, and v_{g} is the group speed.

We consider a charged particle beam (the drive bunch) traveling down the axis of a DL waveguide of length L, and the drive bunch will excite the EM field that carries a traveling wave power P_{w} into the modes of the structure. In the present paper, the drive bunch (or drive bunch train) is considered ultra relativistic (the particle speed equals c, the speed of light in free space).

Let a drive bunch traveling along the $z+$ direction enter the decelerator of length L at moment $t = 0$ and location $z = 0$ (Fig.2(a)). At time t when the bunch is still inside the decelerator (Fig.2(b)), the head of the EM pulse (moving at c) is located at $z = ct$, while the tail of the EM pulse (moving at v_{g}) is located at $z = v_{\mathrm{g}}t$. When the bunch (and the head of the EM pulse) reaches the downstream end ($z = L$) of the decelerator (Fig.2(c)) the time is $t = L/c$ and the tail of the EM pulse has reached the position $z = v_{\mathrm{g}}L/c$. At this moment the generated EM pulse would begin to be extracted by an output coupler (not shown) at

$z = L$, but in this heuristic description we imagine the EM packet propagating out of the end of the decelerator (Fig.2(d)) at time $t = L/v_{\rm g}$. The duration of the EM pulse is the difference between the moment when the bunch reaches the exit ($t = L/c$) and the moment when the tail of the EM pulse reaches the exit ($t = L/v_{\rm g}$). Therefore, the EM pulse duration for single-bunch excitation is given by

$$\tau_{\rm s} = L(1 - u_{\rm g})/v_{\rm g}, \tag{5}$$

where $u_{\rm g} = v_{\rm g}/c$, now we come to consider the field build-up process due to bunch-train excitation. If a second bunch reaches the exit after the first bunch but before the tail of the first EM pulse, then there will be a region where the EM pulses of the two bunches overlap. To create constructive interference (in-phase superposition) of the excited EM fields, the frequency of the excited EM mode (f_0) is chosen to be a harmonic of the bunch frequency $1/T_{\rm b}$, for a train of bunches evenly spaced in time by $T_{\rm b}$.

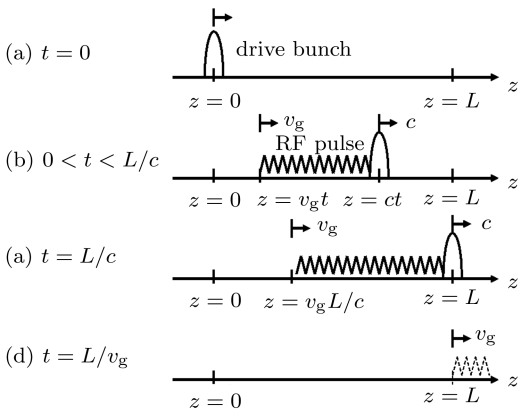


Fig.2. EM pulse due to a single drive bunch, showing a single bunch and excited EM pulse inside the decelerator region $0 \le z \le L$. Panel (a) is for the bunch entering the decelerator ($t = 0$), panel (b) for the bunch and the EM pulse existing inside the decelerator where the head and the tail of the EM pulse travel at different speeds ($0 < t < L/c$), panel (c) for the bunch reaching the exit of the decelerator ($t = L/c$) , and panel (d) for the tail of the EM pulse exiting from the decelerator ($t = L/v_{\rm g}$).

The build-up in time of the longitudinal E-field amplitude due to a bunch train ($E_{0\rm t}$) at the exit of the decelerator ($z = L$) is shown in Fig.3. (Note: this is the field that would be observed by an antenna located at $z = L$ and we have now redefined the time such that $t = 0$ corresponds to the moment when the first bunch arrives at $z = L$.) The EM pulse excited by the individual bunch is labeled with a corresponding number, and the increase of amplitude of the net field (E_{0t}) is due to superposition. The time structure of the EM pulse (at $z = L$) excited by the bunch train consists of a rise-time, a flat-top, and a fall-time, all of which are determined by the overlap of individual single-bunch EM pulse. The rise-time is determined by the number of bunches whose EM pulses overlap with the first EM pulse and is equal to ceiling $(\tau_{\rm s}/T_{\rm b}) - 1$. For example, if the single-bunch pulse length is $\tau_{\rm s} = 2.4$ ns and the bunches are spaced with $T_{\rm b} = 0.769$ ns, then there will be ceiling $(\tau_{\rm s}/T_{\rm b}) - 1 = 3$ trailing bunches whose EM pulses overlap with the first EM pulse. In general, the number of EM pulses that overlap at the exit of the decelerator is $N = \text{ceiling}(\tau_{\rm s}/T_{\rm b})$. From Fig.3, it can be seen for a long bunch train with $n \ge N$, the rise-time $t_{\rm r}$ can be written as

$$t_{\rm r} = (N - 1) \times T_{\rm b}. \tag{6}$$

Similarly, the fall-time is

$$t_{\rm f} = t_{\rm r}. \tag{7}$$

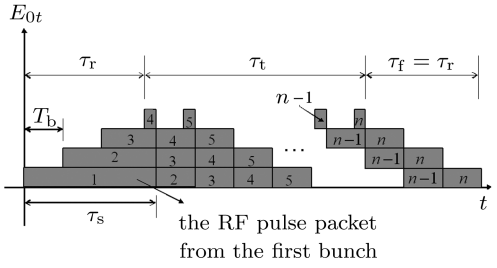


Fig.3. EM pulse due to a drive bunch train and longitudinal E-field amplitude experienced at the exit of the decelerator with bunch train excitation (pulses excited by different bunches are labeled with different numbers).

The steady-state (flat-top) duration of the EM pulse is simply the total length duration minus the rise-time and the fall-time, i.e.

$$\tau_{\rm t} = (n - 1) \times T_{\rm b} + \tau_{\rm s} - 2t_{\rm r}. \tag{8}$$

Note that for a very long train ($n \gg N$) the pulse length is simply $\tau_{\rm t} \approx nT_{\rm b}$.

In this Subsection, we will provide power expressions for the traveling wave excited by a single drive bunch, and a train of drive bunches.

2.2.1. Bunch train drive

When a charged particle bunch (drive bunch) passes through the decelerator, it will excite an EM field, which carries a traveling wave (TW) power $P_{\rm w}$. Let the direction of the TW be along the z axis, the entrance of the decelerator be at $z = 0$, and its exit

be at $z = L$. In the absence of an external power source, all the power comes from the EM field excited by the drive bunch. For each mode, the power decreases along the length of the structure, which can be written as

$$\frac{\mathrm{d}P_\mathrm{w}}{\mathrm{d}z} = -2\alpha_0 P_\mathrm{w}. \tag{9}$$

In the presence of an infinitely long charged particle bunch train with bunch spacing T_b and bunch charge q, a second term representing the power increment per unit length must be added to Eq.(9),[5] thus

$$\frac{\mathrm{d}P_\mathrm{w}}{\mathrm{d}z} = -2\alpha_0 P_\mathrm{w} + \frac{qE_0}{T_\mathrm{b}}, \tag{10}$$

where all the particles are assumed to experience the same decelerator gradient E_0, which means that the bunch length is short compared with the mode wavelength, i.e. $\sigma_\mathrm{z} \ll \lambda_\mathrm{RF}$, so that all particles within the bunch experience the same EM phase.

For nonzero bunch length, the particles within a bunch experience different deceleration gradients, less than or equal to the on-crest gradient E_0, and therefore a bunch form factor Φ is added to Eq.(10), thus

$$\frac{\mathrm{d}P_\mathrm{w}}{\mathrm{d}z} = \frac{qE_0}{T_\mathrm{b}}\Phi - 2\alpha_0 P_\mathrm{w}, \tag{11}$$

where for an ultrarelativistic bunch, Φ is expressed as[7]

$$\Phi = \frac{1}{q}\int_{-\infty}^{+\infty} f(z)\mathrm{e}^{-j\beta_\mathrm{z} z}\mathrm{d}z, \tag{12}$$

where $f(z)$ is the spatial charge distribution for one bunch. In other words, Φ is just the Fourier transform of the charge distribution function $f(z)$. For simplicity, we have dropped the explicit β_z dependence ($\Phi(z) = \Phi$) since the above equations are applied to each mode individually. It is straightforward to show that for a Gaussian spatial bunch distribution $f(z) = q/\sigma_\mathrm{z}\sqrt{2\pi}\cdot\exp\left(-z^2/2\sigma_\mathrm{z}^2\right)$, with root-mean-square (RMS) length σ_z, the form factor is given by

$$\Phi = \exp[-(\beta_\mathrm{z}\sigma_\mathrm{z})^2/2]. \tag{13}$$

Following the derivation by Whittum,[7] for a constant impedance structure (R = constant), we first eliminate P_w from Eq.(11) by using expression (4). Substituting expression (4) into Eq.(11) we can obtain

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{E_0^2}{2\alpha_0 R}\right) = \frac{q\Phi E_0}{T_\mathrm{b}} - \frac{E_0^2}{R}, \tag{14}$$

$$\frac{\mathrm{d}E_0}{\mathrm{d}z} + \alpha_0 E_0 = \frac{q\Phi\alpha_0 R}{T_\mathrm{b}}, \tag{15}$$

$$\frac{\mathrm{d}}{\mathrm{d}z}(E_0\mathrm{e}^{\alpha_0 z}) = \frac{q\Phi\alpha_0 R}{T_\mathrm{b}}\mathrm{e}^{\alpha_0 z}, \tag{16}$$

and

$$E_0(z) = \mathrm{e}^{-\alpha_0 z}\left[E_0(0) + \frac{q\Phi\alpha_0 R}{T_\mathrm{b}}\int_0^z \mathrm{e}^{\alpha_0\tau}\mathrm{d}\tau\right]. \tag{17}$$

We can further simplify this expression by realizing that the bunch must travel some distance before losing energy, and assume that $E_0(0) = 0$. Therefore, expression (17) can be rewritten as

$$E_0(z) = \frac{qR}{T_\mathrm{b}}(1 - \mathrm{e}^{-\alpha_0 z})\Phi. \tag{18}$$

At the exit of the decelerator ($z = L$), the longitudinal E-field amplitude is

$$E_0(L) = \frac{qR}{T_\mathrm{b}}(1 - \mathrm{e}^{-\alpha_0 L})\Phi. \tag{19}$$

Finally, substituting expression (19) into expression (4), one can obtain the power level at the end of the deceleration waveguide as

$$P_\mathrm{t} = q^2\frac{\beta_\mathrm{z}}{4u_\mathrm{g}}\left[\frac{R}{Q}\right]\left(\frac{1 - \mathrm{e}^{-\alpha_0 L}}{\alpha_0 T_\mathrm{b}}\right)^2\Phi^2. \tag{20}$$

Furthermore, when the decelerator is lossless ($\alpha_0 = 0$), expression (20) can be modified into

$$P_\mathrm{t} = q^2\frac{\beta_\mathrm{z}}{4u_\mathrm{g}}\left[\frac{R}{Q}\right]\left(\frac{L}{T_\mathrm{b}}\right)^2\Phi^2. \tag{21}$$

2.2.2. Single drive bunch

The power level generated by a single bunch can be obtained by modifying expression (21) if we arrange for the net EM pulse to be constant. This can be done by changing the decelerator length L, such that the single-bunch pulse duration τ_s is exactly the same as the bunch spacing T_b. In this case, the individual EM pulses exit from the decelerator, stacked one after another without overlap or a gap between them, according to the illustration in Fig.3. Therefore, the power level calculated from expression (21) will be the same as that excited by a single bunch. In other words, by replacing T_b with τ_s in expression (21), we can obtain the power level at the exit of a lossless decelerator, excited by a single bunch, as

$$P_\mathrm{s} = q^2\frac{\beta_\mathrm{z}u_\mathrm{g}}{4}\left[\frac{R}{Q}\right]\left(\frac{c}{1-u_\mathrm{g}}\right)^2\Phi^2, \quad (0 \le t \le \tau_\mathrm{s}). \tag{22}$$

For a loss ($\alpha_0 \neq 0$) structure, expression (22) can be modified into

$$P_\mathrm{s} = q^2\frac{\beta_\mathrm{z}u_\mathrm{g}}{4}\left[\frac{R}{Q}\right]\left(\frac{c}{1-u_\mathrm{g}}\right)^2\Phi^2\mathrm{e}^{-2\alpha_0 v_\mathrm{g} t}, \quad (0 \le t \le \tau_\mathrm{s}), \tag{23}$$

where $t = 0$ is the moment when the bunch exits from the decelerator, i.e. the moment when the head of the excited EM pulse exits from the decelerator.

3. Design of the power generation device using DL waveguide

This power generation device consists of two parts: a deceleration waveguide and an output coupler. In this section first we give the design of the deceleration waveguide, by performing a CST MAFIA simulation of power generation; then we present the design of the output coupler, whose role is to extract the generated power out of the structure as efficiently as possible.

3.1. Design of deceleration waveguide

In the deceleration waveguide shown in Fig.1, the LSM_{11} mode has the strongest interaction with an on-axis beam, therefore it is chosen as the deceleration mode, whose complete solution is given in Ref.[4]. The frequency of the mode at which it can be synchronous with the beam, is chosen to be 7.8 GHz. The beam channel dimensions are set according to the typical transverse size of the flat driving beam, and other parameters are adjusted to move the synchronous frequency to 7.8 GHz, where the calculation is performed by using the Matlab. The EM pulse length is chosen as the desired EM pulse length in single bunch excitation, and the number of stacked EM pulses adopts that in bunch train excitation. The final design is a tradeoff among various constraints, and the parameters are listed in Table 1.

We use the first method to calculate the excited EM field gradient from Eq.(2). The longitudinal E-field of LSM_{11} mode is shown in Fig.4. Here, an electron bunch with $\sigma_z = 2$ mm and $q = 1$ nC located at $x_0 = 0$ and $y_0 = 0$ is traversing along the axis at the speed of light in a rectangular DL waveguide. We can easily find the amplitude of the longitudinal E-field to be 0.117 MV/m. Meanwhile, according to the relation between EM field and power flow, the excited power at the downstream end of the structure can be calculated from the gradient with the mode pattern, and the calculated power is 1.83 kW. By using the second method, the calculated amplitude of the longitudinal E-field is 0.120 MV/m, and the calculated power is 2.12 kW. Apparently, the results obtained from method I and method II are in agreement with each other.

Table 1. Parameters for the rectangular DL waveguide.

RF frequency	f	7.8 GHz
beam channel height	$2a$	6.0 mm
dielectric-loaded waveguide height	$2b$	12.0 mm
dielectric-loaded waveguide width	w	28.4 mm
dielectric-loaded waveguide length	L	80 mm
relative permittivity of the dielectric	ε_r	10
relativistic group speed of RF mode	v_g	0.11
loss tangent of dielectric	δ_d	5×10^{-4}
wall quality factor	Q_w	4135
total quality factor	Q	1348
"R over Q" per unit length	$[R/Q]$	5.043 kΩ/m

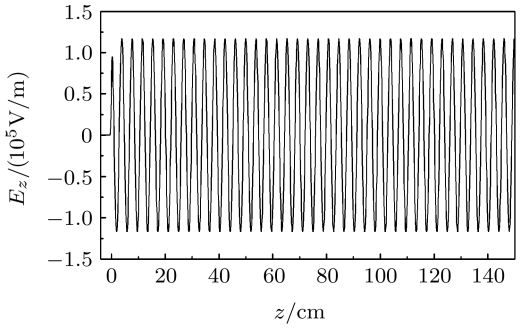


Fig.4. Calculated longitudinal E-field by using the field analysis method with $a = 3$ mm, $b = 6$ mm, $w = 28.4$ mm, $\varepsilon_r = 10$, $\sigma_z = 2$ mm, and $q = 1$ nC.

In order to confirm the analytical result here, a commercial EM simulation tool CST MAFIA is used for the same structure, and the result is shown in Fig.5, where the amplitude of the longitudinal E-field is 0.119 MV, close to the value calculated from expression (2).

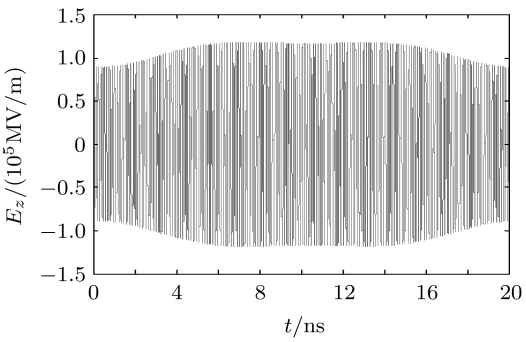


Fig.5. Simulated longitudinal E-field by using the MAFIA code.

With the 100 nC single bunch excitation, the induced gradient will be 11.71 MV/m, corresponding

to 17.05 MW of power generated. If a bunch train with a bunch frequency 1.3 GHz and 100 nC/bunch is used as the driving beam, the excited gradient will be 33.14 MV/m, corresponding to 160 MW of power generated. In the bunch train excitation, at least four bunches are needed for obtaining the above values of gradient and power.

3.2. Design of the output coupler

An efficient output coupler is important for power extraction. The length of the generated EM pulses is expected to range from 10 to 50 ns, depending on the length of the bunch train. Therefore, in order to efficiently extract the generated power contained in these short pulses, the bandwidth of the output coupler needs to be well above 100 MHz. In this section, the design for a wide band 7.8 GHz output coupler is described.

Figure 6 shows the geometry and the dimensions of the output coupler. This Y-shaped coupler has one input port and two symmetric output ports. The input port has the same cross-section as that of the DL waveguide, and the two output ports are hollow rectangular waveguides. The coupler is able to convert the LSM_{11} mode inside the DL waveguide into the TE_{10} mode in the output waveguides. The dielectric slabs are tapered around the output ports for smooth transition. To minimize reflection, the angle between the two branches and the length of the tapered section are adjusted. The coupler has been simulated and optimized with CST Microwave Studio, and the S-parameters (where S stands for scattering) of the final design are plotted in Fig.7. At 7.8 GHz, the S_{21} reaches –3.27 dB and the S_{31} reaches –3.22 dB. Both transmission coefficients are close to the ideal value

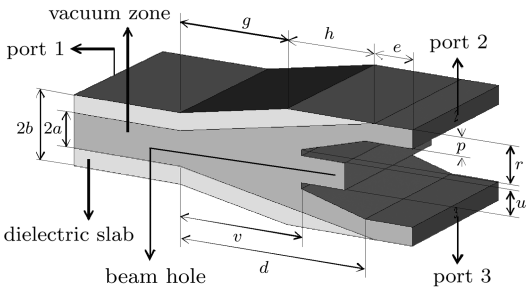


Fig.6. CST microwave studio geometry of the LSM_{11}-TE_{10} coupler with the background material set to satisfy the perfect electrical conductor boundary condition ($d = 33.9$ mm, $g = 20.0$ mm, $h = 16.2$ mm, $e = 7.0$ mm, $p = 3.1$ mm, $r = 9.7$ mm, $u = 2.66$ mm, $v = 22.7$ mm).

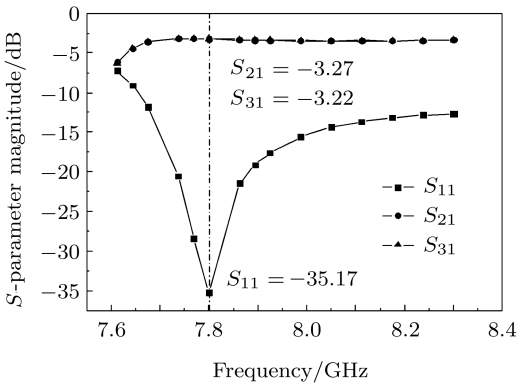


Fig.7. Simulated S-parameters of the output coupler.

–3 dB. Accordingly, the power coupling efficiency is 94%. The reflection coefficient S_{11} is –35 dB at 7.8 GHz, and it is less than –15 dB in a range from 7.7 to 8.0 GHz. The bandwidth of the coupler is good enough for pulses with lengths on the order of 10 ns.

4. summary

In this paper, power generation using an electromagnetic mode in a rectangular structure with a non-uniform deceleration gradient over the transverse plane is discussed. The calculation of generated power by an ultra-relativistic beam is described. We have designed a 7.8 GHz power generation device based on a rectangular DL waveguide, which is able to generate a 160 MW power from a train of electron bunches with 100 nC charge per bunch. An output coupler has also been designed to extract power to an output waveguide, with a power coupling efficiency of 94% at 7.8 GHz. This power generation device shows its potential application to a high charge rectangular beam with large transverse beam size.

Acknowledgment

The authors would like to thank Dr. Geoff Waldschmidt at the Argonne National Laboratory (ANL) Advanced Photon Source for his helpful suggestion on the MAFIA simulations, and thank Dr. Paul Schoessow at Euclid Techlabs for his kind help in writing this paper.

References

[1] Flesher G and Cohn G 1951 *IEEE Trans. Plas. Sci.* **70** 887

[2] Lu Z G, Gong Y B, Wei Y Y and Wang W X 2006 *Chin. Phys.* **15** 2661

[3] Zou P, Gai W, Konecny R and Sun X 2000 *Rev. Sci. Instr.* **71** 2301

[4] Xiao L, Gai W and Sun X 2001 *Phys. Rev.* E **65** 016505

[5] Wang C and Hirshfield J L 2004 *Phys. Rev. ST Accel. Beams* **7** 051301

[6] Gao F, Conde M E, Gai W, Konecny R, Liu W, Power J G, Yusof Z and Wong T 2008 *Phys. Rev. ST Accel. Beams* **11** 041301

[7] Newsham D and Smirnov A 2002 *AIP Conf. Proc.* **6**47