Design of an on-line measuring system for 0.14THz high-power terahertz pulse

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Abstract. An on-line measuring system, including an aperture-coupling structure and a novel high-power pulse detector, is proposed in this paper to measure the output pulses from high-power 0.14THz surface wave oscillator (SWO). At first a T-type coupling structure between the TM01 mode of circular waveguide with radius of 6mm and TE10 mode of rectangular waveguide WR6 is designed. Based on loose coupling theory, the coupling degree of this structure is derived and calculated, reaching about -47dB with the aperture radius of 0.4mm and length of 0.5mm. The reasonable coincidence is found between the theoretical computation and numerical simulation employing the three-dimensional finite difference time domain method. Then a novel high-power terahertz pulse detector based on hot electron effect in semiconductors is developed for the detection of output pulses from T-type coupling structure. With hot electron theory, the working principle of the detector is elucidated, also its sensitivity is simply analyzed, showing that this detector is capable of handling the pulse power as high as 2kW. The present 0.14THz on-line measuring system would be convenient to monitor the terahertz pulse shape and pulse power during the application researches of SWO besides increasing the accuracy of its pulse power measurement.

1. Introduction

With the developments of terahertz technologies, there have been considerable demands on the compact high-power terahertz radiation sources due to their unique applications in the military security, fundamental science, communications, and so on [1]. However, typical photonic based and solid-state sources have rather low energy conversion rate, yielding output power with the maximum magnitude of only tens of watts, while the free electron laser based on vacuum electronics has the largest output power but also system size. So the other two kinds of vacuum electronic devices, namely relativistic Cerenkov radiation generators and gyrotrons, offer the promising candidates and become hot researches for their high-power output and compact configurations [2,3].

Recently, our research group has successfully designed and tested a 0.14THz high-power surface wave oscillator (SWO) [4], a type of relativistic Cerenkov radiation generators. According to the preliminary experimental results, the output pulses from SWO have the characteristics of high
frequency, high-power, and nanosecond pulse duration, thus, their measuring methods and systems are needed. To directly detect the output pulses, this paper presents the design of an on-line measuring system for our 0.14THz SWO, which is composed of a T-type aperture-coupling structure and a novel high-power pulse detector. Using the loose coupling theory, the coupling degree of the designed T-type aperture-coupling structure is analyzed and calculated. Then a novel 0.14THz high-power pulse detector based on hot electron effect in n-Si is introduced with detailed illumination on the design of the sensing element and working principle of detector.

2. Aperture-coupling system

2.1. Coupling formulas of a single cylindrical hole

The small apertures are usually used to partially couple electromagnetic (EM) wave energy from output waveguides of sources for following measurements in the on-line measuring systems [5,6]. In general, the apertures are positioned on the common waveguide walls between different waveguides, schematically shown in figure 1. When the source wave in waveguide below encounters the aperture, wave diffraction occurs, exciting positive and negative waves simultaneously in waveguide above and changing the EM field distribution in waveguide below. According to the loose coupling theory, the aperture-coupling coefficient \( A \) of electromagnetic field in excited waveguide can be determined by the expression [7]

\[
A^\pm = (-1)^\pm \frac{j\pi}{2} \left( \mu p^* \hat{H}_0^\pm \hat{H}_1^\mp + \mu p^* \hat{H}_2^\mp \hat{H}_1^\mp + \varepsilon p E^\pm_0 E^\mp_0 \right)
\]

(1)

where the superscripts “+” and “−” denote positive wave and negative wave, respectively, the subscripts 1 and 2 separately represent parameters in source waveguide and excited waveguide, \( f \) is the frequency of EM wave, \( \varepsilon \) is the permittivity of medium inside waveguide, \( \mu \) is the permeability, \((u,v,n)\) is the local coordinates at the aperture where \( n \) is normal direction of the cross-section of the aperture, \( p^* \) are the tangential magnetic polarizability of the aperture, \( p \) is the normal electrical polarizability, \( \hat{H}^\pm \) and \( \hat{E}^\pm \) are normalized magnetic and electric fields at the aperture neglecting the effect of the hole on the EM field in waveguides, respectively. For a cylindrical hole with radius \( r \) and length \( h \), the \( p^* \) and \( p \) are [7]

\[
p^* = 4r \left| 0.8 - \left( 3.41 \sqrt{\frac{\pi}{u}} \right) \right| / 3, \quad p = 2r \left| 0.8 - \left( 2.61 \sqrt{\frac{\pi}{u}} \right) \right| / 3
\]

(2)

where \( c \) is the speed of light. Finally, the coupling degree \( C \) of the hole is calculated by

\[
C^\pm = 10 \lg \left| A^\pm \right| = 20 \lg \left| A^\pm \right|
\]

(3)

Figure 1. Sketch map of aperture-coupling on the common waveguide wall

2.2. Design and analysis of a T-type aperture-coupling structure

Suppose that the 0.14THz SWO is operated near the \( \pi \) mode of TM\(_{01}\) wave and has an overmoded cylinder waveguide output [4], the aperture-coupling structure should be able to effectively couple the
energy from TM\textsubscript{01} mode of circular waveguide to the TE\textsubscript{10} mode of rectangular waveguide WR6. Through the analysis of EM field distribution at both sides of the aperture, a T-type aperture-coupling structure, where one port of waveguide WR6 is on the wall of cylinder waveguide and a cylindrical hole in the center of the interface penetrates it, is designed for the sake of easy fabrication and installation, schematically shown in figure 2. Actually the angle between the direction along the narrow wall of rectangular waveguide and the length of the cylinder waveguide, which is denoted as $\theta$ in the following analysis, would be adjustable to acquire optimal coupling degree.

The selected coordinates in each waveguide and at the aperture are also displayed in figure 2. Obviously, the local coordinates $(u, v, n)$ correspond to the coordinates $(\phi, z, \rho)$ in cylinder waveguide while coordinates $(u, v)$ and $(x, y)$ lie at an angle of $\theta$ with $n$ and $z$ coinciding in rectangular waveguide. Consequently, the EM field components in Eq. (1) can be replaced, yielding that,

$$A^\pm = (-1)^\pm \frac{j\pi f}{2} [\mu p_s (H_x^\pm \sin \theta - H_y^\pm \cos \theta) H^\prime_{\phi} + \mu p_r (H_x^\pm \sin \theta + H_y^\pm \cos \theta) H^\prime_{\rho} + e p E^\prime_{\rho}]$$ (4)

For TM\textsubscript{01} mode in cylinder waveguide, the EM field components normalized to the power flow are derived as follows:

$$\begin{align*}
E_\rho &= -j\frac{2\beta_{01}}{\sqrt{\omega \varepsilon \pi R}} J_0(x_{01}/R) e^{-j\beta_{01}z}, \\
E_z &= \frac{\sqrt{2x_{01}}}{\sqrt{\omega \rho_0 \varepsilon R^2}} J_0(x_{01}/R) e^{-j\beta_{01}z}, \\
H_\theta &= -j\frac{2\omega}{\sqrt{\beta_{01} \pi R}} \frac{J_0(x_{01}/R)}{J_0(x_{01})} e^{-j\beta_{01}z}, \\
E_\phi &= H_\rho = H_z = 0
\end{align*}$$ (5)

where $\omega$ is the angular frequency of EM wave, $\beta_{01}$ is the longitudinal wavenumber of TM\textsubscript{01} mode, $R$ is the radius of the cylinder waveguide, $J_0$ is zero order Bessel function, $x_{01}$ is the first root of $J_0=0$, and $J_0$ is its first differential. The normalized EM field components for TE\textsubscript{10} mode in rectangular waveguide are

$$\begin{align*}
E_y &= -\frac{\beta_{10}}{\sqrt{\omega \mu \varepsilon ab}} \sin(\pi a) e^{-j\beta_{01}z}, \\
H_x &= \frac{\beta_{10}}{\sqrt{\omega \mu \varepsilon ab}} \sin(\pi x) e^{-j\beta_{01}z}, \\
H_z &= \frac{2\pi}{\sqrt{\omega \mu \varepsilon ab}} \cos(\pi x) e^{-j\beta_{01}z}, \\
E_x &= E_z = H_y = 0
\end{align*}$$ (6)

where $a$ and $b$ are the length of the wide wall and narrow wall of rectangular waveguide, respectively, $\beta_{10}$ is the longitudinal wavenumber of TE\textsubscript{10} mode, and $\eta_{TE10}$ is the wave impedance. Substituting Eqs. (5) and (6) to (4), one can get

$$|A^\pm| = (-1)^\pm \frac{j\pi f \mu p_r^*}{2} H_x^{\prime\prime} H_y^{\prime\prime} \sin \theta = \frac{2r^3}{3Re} [\frac{1}{\sqrt{ab \pi}} \frac{2}{\sqrt{\beta_{01}}} \sqrt{\beta_{10}}]$$ (7)
In terms of the structural characters of the T-type aperture-coupling, the negative wave excited in rectangular waveguide would be fully reflected by the metal wall of the cylinder waveguide, then superimposed on the positive wave. Thus, the total field coupling coefficient is

$$|d| = \frac{4r^3}{3Re} \left[ 10^{-0.8\sqrt{-\frac{(3.41f/c)h}{r}}/r} \right] \frac{\omega}{ab\pi} \sqrt{\frac{2}{ab\pi} \sqrt{\frac{\beta_{01}}{\beta_{01i}}}}$$

(8)

Evidently there is only magnetic coupling in the designed T-type aperture-coupling structure, and the maximum coupling degree is achieved when $\theta$ is 0, namely the narrow wall of the rectangular waveguide parallels the longitudinal direction of cylinder waveguide. In this case, the coupling degree is obtained

$$C = 20\log\left(\frac{4r^3}{3Re} \left[ 10^{-0.8\sqrt{-\frac{(3.41f/c)h}{r}}/r} \right] \frac{\omega}{ab\pi} \sqrt{\frac{2}{ab\pi} \sqrt{\frac{\beta_{01}}{\beta_{01i}}}}\right)$$

(9)

In our design, the following geometric parameters of the waveguides and aperture are chosen: $a=1.651\,\text{mm}$, $b=0.8255\,\text{mm}$, $R=6\,\text{mm}$, $r=0.4\,\text{mm}$, and $h=0.5\,\text{mm}$. The coupling degree calculated by Eq. (9) in the frequency range 0.113-0.173THz is shown in figure 3, represented by dotted line. Along with the increase of the frequency the coupling degree increases approximately linearly, ranging from -52dB to -42dB. To validate the theory analysis above, a three-dimensional EM finite-difference time-domain method [8] is used to numerically simulate the T-type aperture-coupling structure. The simulation result is also shown in figure 3 corresponding to the solid line, agreeing with the theory calculation fairly well. A discrepancy no more than 1.5dB is found probably caused by the following two reasons: 1)the attenuation of polarizability along the longitudinal direction of the hole in Eq. (2) is an approximate estimation [7]; 2)the cylinder waveguide with radius of 6mm belongs to overmoded waveguide and has more than 200 propagation modes in 0.14THz frequency range, leading to other modes besides TM$_{01}$ mode excited in cylinder waveguide by the effect of the hole on the waveguide wall.

Figure 2. Schematic diagram of T-type aperture-coupling structure

Figure 3. Coupling degree of T-type aperture-coupling structure

3. Novel high-power terahertz pulse detector

Based on the simulation results of our SWO, it has an output power of at least several megawatts around the frequency of 0.147THz [4]. Accordingly, the coupled energy from SWO employing the foregoing T-type aperture-coupling structure would get the power level of tens of watts, much bigger than the bearing power level of conventional diode detector. So large attenuation is needed, resulting in the accuracy decrease of terahertz pulse power measurement.
To solve this problem, a novel high-power terahertz pulse detector based on hot-electron effect in semiconductors gives an alternative device, illustrated in figure 4(a). Referred to the resistance sensor in W-band [9], the developed detector in 0.14THz frequency band comprises a standard waveguide WR6, a sensing element made of n-type silicon, and a bias constant current source. The sensing element, key component of this detector, is mounted on the center of wide wall of the waveguide WR6, the cross-section of which is shown in figure 4(b). Two same n-Si cubes with ohmic contact are shorted with copper foil on the upper contact, while the bottom contact of one cube is grounded with wide wall and the other is isolated from it. Connected with a constant current source, the feeding and output signal measurement of the sensing sample are fulfilled.

![Figure 4](image)

**Figure 4.** (a)The schematic diagram of the novel detector and (b) cross-section of the sensing element

At first, the constant current $I_0$ is applied on the sensing element, forming a DC voltage drop $U_0$. When a high-power 0.14THz pulse propagates within the waveguide WR6, the TE$_{10}$ mode is excited, where the electric field parallels the direction along the narrow wall. According to the hot-electron effect in semiconductors [10], the high electric field heats the electrons in sensing element, producing so-called hot electrons and resulting in the increase of its resistance. Simultaneously, the voltage drop on the sensing element changes with a shape the same as the envelop of the terahertz pulse, namely a voltage pulse with amplitude of $U_s$ is superposed on initial voltage $U_0$. Therefore, so long as the Joule heat effect on the sensing element caused by measured pulse is ignorable, this voltage pulse fully indicates the envelop shape and amplitude of the 0.14THz high-power pulse. With careful calibration in 0.14THz frequency band, the designed detector can be used to measure the power of 0.14THz high-power pulses.

Through simple circuit analysis of the detector, the relation between $U_s$ and $U_0$ is written as

$$
\frac{U_s}{U_0} = \frac{I_0 \Delta R_0}{I_0 R_0} = \frac{\Delta R_0}{R_0} = \zeta P
$$

where $R_0$ is the initial resistance of the sensing element, $P$ is the power of the measured pulse, and $\zeta$ is the relative sensitivity of the detector, which is the function of the frequency and power of the measured pulse. When $P$ is rather small, the heated electrons are called warm electrons. In this case, the relative sensitivity is independent of $P$ [9], just like the diode detector working in the region of square law.

The researches on the hot-electron effect in n-Si show that the saturation field strength is about 20kV/cm and the field strength in warm electron region is less than 1kV/cm [10]. However, there is atmospheric breakdown in waveguide WR6, and the maximum electric field strength is about 18kV/cm considering the standing wave and atmospheric humidity in waveguide [11]. Thus the detector here could bear the electric field with maximum strength of 18kV/cm while its linear working region is that the electric field strength is no more than 1kV/cm. For TE$_{10}$ mode in an empty rectangular waveguide, the maximum electric field is described by
where $f_c$ is the cut-off frequency of TE_{10} mode in waveguide. Substituting the corresponding electric field to Eq. (11), we obtain that the maximum power that the detector can handle and works in the linear region is about 2kW and 7W, respectively. As the distributed capacitance and inductance are very small in the sensing element, the response time of this detector is mainly decided by the pickup circuit of the output voltage pulse. With appropriate design on the detecting circuit, the novel detector could directly measure the nanosecond pulses with power as high as 2kW in 0.14THz frequency band. The manufacture and calibration technologies of the detector are under research now.

4. Conclusions
In this work, an on-line measuring system for high-power 0.14 THz SWO is designed, which is composed of the T-type aperture-coupling structure and novel high-power pulse detector for 0.14THz frequency band. With aperture radius of 0.4mm and length of 0.5mm, the T-type aperture-coupling structure has the coupling degree from -52dB to -42dB, attested by the three-dimensional EM finite difference time domain method. Then a novel detector based on hot-electron effect in n-Si is proposed. The capability of handling the maximum power of about 2kW is highlighted with detailed analysis on the working principle of the detector. Combining the novel detector with T-type aperture-coupling structure, the designed 0.14THz on-line measuring system can directly measure the output pulses from our megawatt-class SWO without attenuation, increasing the accuracy of the power measurements, and also it is very suitable to monitor the terahertz pulse shape and pulse power during the applications of SWO.

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