Regenerated amplification of terahertz spoof surface plasmon radiation

Juan-Feng Zhu, Chao-Hai Du, Lu-Yao Bao and Pu-Kun Liu

State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronics, Peking University, Beijing, 100871, People’s Republic of China

1 Authors to whom any correspondence should be addressed.
E-mail: duchaohai@pku.edu.cn and pkliu@pku.edu.cn

Keywords: regenerated amplification, spoof surface plasmon, terahertz radiation, Fabry–Perot cavity

Abstract
Regenerated amplification induced by a Fabry–Perot (F–P) cavity is introduced to enhance the interaction efficiency of the free-electron-driven spoof surface plasmon. A direct-current electron beam flies above the meta-grating surface and seeds noise-level plasmonic waves. This weak signal experiences multiple back-and-forth regenerated amplifications in the F–P cavity loaded grating system, and the system outputs a pulsed radiation when the signal leaves the cavity. When compared with the condition without the F–P cavity, the equivalent beam-wave interaction length is effectively extended, and the interaction efficiency is improved by orders of magnitude. The proof-of-principle scheme is verified in both backward-wave and forward-wave modes using the particle-in-cell simulation. This scheme is promising for developing high-efficient on-chip terahertz free-electron radiation sources.

1. Introduction

Terahertz (THz) wave spectrum locates between the microwave and far infrared regions and becomes more and more attractive for various applications, including high-data-rate communication, bio-medicine imaging, immunosensing, security inspection, sensitivity-enhanced nuclear magnetic resonance (NMR), and so on [1–9]. Room-temperature efficient THz sources play key roles in developing THz technologies and applications. Vacuum electronic devices (VEDs), such as extend interaction oscillators [10], backward-wave oscillators [11], traveling-wave tubes (TWTs) [12], and gyrotrons [13], can generate high radiation power from watt to kilowatt level. In recent years, the THz VEDs based on the spoof surface plasmon (SSP) becomes promising due to the intriguing characteristics of SSP, such as the local resonant effect, strong near-field confinement. Thus it brings new possibilities of realizing better performance and higher operation frequency than the traditional slow-wave interaction systems [14–19].

There are a number of works devoted to investigating the beam-wave interaction mechanism. Generally, the methods to improve the interaction efficiency fall into several categories. Firstly, a prebunched free electron beam (FEB) is used to improve the interaction efficiency [20]. Secondly, elevating the field intensity in the FEB channel is an effective way for high efficient interaction as well. Various circuits such as the doubly metallic gratings [21], composite sandwich structure [22], and multiple stacked layers [23] are proposed to improve the field intensity in interaction region. Thirdly, multi-beam wave interaction is also a convenient way to improve the efficiency. The interaction systems including two and nine electron beams have been studied [24, 25]. Besides, the graded depth grating is also utilized to keep the after-interaction synchronization between the FEB and SSP wave [26]. Although some exploit has been achieved, it still challenging for experimental realization. Additionally, developing on-chip THz radiation sources has a tendency in recent years [27, 28]. Since the current of FEB is weak in an on-chip THz radiation system, a long interaction circuit is crucial to extract the energy from FEB. Nevertheless, it is still insurmountable to achieve a high rate of transmission for an FEB traveling through the micro-interaction system in practice.

© 2019 The Author(s). Published by IOP Publishing Ltd on behalf of the Institute of Physics and Deutsche Physikalische Gesellschaft
In this paper, a robust approach is proposed to enhance the beam-wave interaction efficiency based on a short interaction circuit. Inspired by the lasers in photonic devices, the interaction system based on a Fabry–Perot (F–P) cavity loaded metallic grating is introduced. Compared with the previous work [19], the Poynting flux experiences multi-pass reflections and regenerated amplification within the F–P cavity. This mechanism is verified by the particle-in-cell (PIC) simulation in backward-wave and forward-wave modes, respectively. By this way, the equivalent beam-wave interaction length is far longer than the physical circuit length, which is an effective way to enhance the beam-wave interaction efficiency. Furthermore, it provides a practical way to generate high-power THz radiation from a short interaction circuit system especially from an on-chip THz radiation source.

2. Theory and simulation

The conceptual system is illustrated in figure 1. The grating has uniform grooves with width \( a \), period \( p \), and depth \( h \). The length of the plasmonic grating is \( L \). A pair of F–P mirrors is placed above the plasmonic grating to extend the equivalent interaction length. The length of F–P cavity is \( L_c \). The gap between the grating and the F–P cavity is \( g \). The direct-current (DC) FEB flies above the grating and passes through the gap between F–P cavity and plasmonic grating. The voltage and current of the FEB are \( U \) and \( I \), respectively.

2.1. Dispersion relation analysis

In order to explore the physical characteristics of this system, the dispersion behavior and slow-wave characteristics of SSP are primarily studied. Considering that the SSP mode on the plasmonic grating is a quasi-two-dimensional electromagnetic excitation, we assume the width of this grating is smaller than the light speed \( c \) in vacuum, the continuous FEB can be equivalent to an anisotropic plasma medium [29], and the relative permittivity \( \varepsilon_r \) is depicted in equation (1)

\[
\varepsilon_r = \text{diag}(0, 0, \varepsilon) ,
\]

where \( \varepsilon = 1 - \frac{\omega^2}{\omega_p^2} = 1 - \frac{\rho_e}{\varepsilon_m^0} \), \( \omega_p \) is the effective plasma frequency, \( \rho_e \) is the charge density, \( \varepsilon_m^0 \) is the vacuum permittivity, \( \varepsilon \) is the electron charge, \( \varepsilon_m \) is the electron mass, \( \nu_e \) is the velocity of electron beam, \( \omega \) is angular frequency, \( k_z \) is longitudinal wave vector. By this way, the whole space could be divided into three regions according to the boundaries. Then the field expressions in each region can be obtained. As metals behave as a near perfect electric conductor (PEC) in the THz region [14]. The hot dispersion relation with the FEB is obtained according to the mode matching method by applying the electric and magnetic field boundary conditions based on the PEC model as equation (2)

\[
a P_{n=\infty} \sum_{n=0}^{\infty} \varepsilon_n \frac{M_1 - M_2}{M_1 + M_2} \sin^2 \left( \frac{k_{zm} a}{2} \right) = \frac{\varepsilon_0}{k} \cot(k h),
\]

where \( M_0 = \frac{1}{2} \varepsilon_m^0 \left( 1 + \frac{\varepsilon_m^0}{\varepsilon} \right) \), \( M_1 = \frac{1}{2} \varepsilon_m^0 \left( 1 - \frac{\varepsilon_m^0}{\varepsilon} \right) \), \( \varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2} \), \( \tau_m = \sqrt{\frac{\varepsilon_0 (k_{zm}^2 - k_z^2)}{k_{zm}^2}} \), \( k_{zm} = k_z + 2n \pi / p \) is the longitudinal wave the nth harmonic mode, \( n = 0, \pm 1, \pm 2, \pm 3, \ldots \), \( k = \omega / c \) is the wave vector in free space, and \( c \) is the light speed in space. The interaction frequency can be obtained by solving the sophisticated equation (2). For simplification, the equation (2) degenerates into two equations expressed by equations (3), (4) that represent the dispersion characteristics of SSP wave and the FEB, respectively. Moreover, the velocity of the FEB is depicted as equation (5):
The structural parameters are shown in Table 1, and the dispersion diagram is presented in Figure 2. The interaction frequency \( \omega = \frac{\nu_e k_z}{2} \) (i.e. the frequency of the intersection point between the dispersion curve of SSP and FEB line) is determined by the structural parameters \( a, p, h \), and the beam voltage \( U \). As the structural parameters do not change, the interaction frequency varies during FEB voltage tuning. Additionally, the dispersion characteristic of plasmonic grating is studied by numerical simulation based on the finite-difference time-domain software (CHPIC), and the result is shown as a pink line [30]. The theoretical analysis is in good agreement with the simulation result. Besides that, the interaction impedance and the group velocity are also calculated, which are shown in the inset. Generally, the coupled impedance is a key factor related to the beam-wave interaction. The beam-wave interaction efficiency is proportional to the coupled impedance, and high interaction impedance helps electromagnetic wave extract energy from the FEB. The interaction impedance \( K_n \) is calculated by equation (6):

\[
K_n = \frac{E_{zn}^2}{k_{zn}^2 P_a}
\]

where \( E_{zn} \) is the amplitude of the \( n \)th harmonic mode, and \( P_a \) is the sum of power fluxes along the plasmonic surface. When the interaction frequency approaches the cut-off frequency, the coupled impedance increases dramatically. The group velocity slows down and almost vanishes. The field intensity increases, owing to the accumulation of electromagnetic energy induced by the slowing group velocity.

### 2.2. PIC simulation results

Given the previous theoretical analysis, the proposed THz radiation source utilizes the FEB to excite the SSP wave confined along the surface of the metallic grating. When the phase velocity of SSP wave matches the velocity of FEB, the beam-wave synchronization occurs and the SSP wave extracts the energy of FEB.

---

**Table 1.** Parameters of the schematic model.

| Parameters | Value |
|------------|-------|
| Period \( p \) | 20 \( \mu \)m |
| Width \( a \) | 10 \( \mu \)m |
| Deep \( h \) | 65 \( \mu \)m |
| Gap \( g \) | 5 \( \mu \)m |
| Circuit length \( L \) | 10 mm |
| Cavity length \( L_c \) | 9 mm |

\[
\frac{1}{\tau_n} \sum_{n=-\infty}^{+\infty} \sin c^2 \left( \frac{k_{zn} a}{2} \right) = \frac{P_a}{ak} \cot(kh), \quad (3)
\]

\[
\omega = \nu_e k_z, \quad (4)
\]

\[
\nu_e = c \sqrt{1 - \left( \frac{1}{1 + \frac{eU}{mc^2}} \right)^2}, \quad (5)
\]
The proposed mechanism is verified by the PIC software CHIPIC [30]. The cut-off frequency of the SSP mode is about 1 THz, and the corresponding wavelength is about 300 μm. In order to make a precise investigation, the maximum grid length in x and z direction are set 2 μm. A DC FEB is used in the simulation model, and the width of the FEB is 10 μm. As the SSP mode curves with metal and PEC have a relative small influence on the working frequency [31, 32], and the PEC model is utilized in our simulation model, which is a universal method in the THz region [14]. A longitudinal magnetic field of 2 T is added to ensure the electron move straightly along the z axis. The model is surrounded by the perfectly matched layers. The reflections caused by the boundaries are minimized and can be ignored approximately [30, 33]. The beam-wave interactions in the backward-wave and the forward-wave modes are different, which are discussed in the following.

2.2.1. Beam-wave interaction in the backward-wave region

When $U < 4.6 \text{kV}$, the backward SSP mode is excited as the interaction point lies in the backward-wave region. The current of the DC electron beam is set as 20 mA. There is an internal feedback in the backward-wave interaction, and the required working current decreases. The current of the DC FEB is set as 20 mA. The Poynting flux is excited near the right end of the plasmonic grating and increases towards the left end to approach saturation. On the contrary, the Poynting flux propagates backwardly. In order to make a thorough analysis about the physical mechanism, the beam-wave interaction under different voltages are studied. The distributions of Poynting flux along the circuit at different working voltages are presented in figure 3. With the working voltage increasing from 3 to 4 kV, the coupled impedance is increased, and the interaction efficiency is improved consequently. This can be verified by the maximum power and growth rate. The maximum power increases from 1.2 to 4.2 W, and the growth rate increases from 21.7 to 26.70 dBm mm$^{-1}$. The interaction efficiency increases from 2% to 4%.

However, the interaction efficiency is still low due to the finite length of interaction circuit, which is a commonplace in VEDs. An effective method is required for high efficiency. Generally speaking, the VEDs have a resemblance to the lasers. The light from the medium, produced by spontaneous emission, is amplified via the light–matter interaction within gain medium in lasers. It always requires an optical cavity, where the laser radiation can pass and circulate a gain medium more than one time to compensate optical losses. Consequently, the amplified spontaneous emission extracts significant power in multiple passes through the gain medium before exiting the cavity. Inspired by this kind of mechanism, we propose a F–P cavity loaded grating system to extend the equivalent circuit length and enhance the beam-wave interaction efficiency. The time-space Poynting flux distributions are shown in figure 4. The Poynting flux bounces back-and-forth in multiple times within the F–P cavity. Compared with the beam-wave interaction without the cavity, the radiation intensity is improved significantly. The maximum peak power is enhanced more than 10, 4 and 1.55 times larger than that without the cavity at $U = 3, 3.5$ and 4 kV, respectively. The variations arise from the different number of back-and-forth trips during the same simulation time. The Poynting fluxes complete 8, 4 and 2 back-and-forth trips in 100 ns at $U = 3, 3.5$ and 4 kV, respectively, which is caused by the different group velocities. The interval $t_p$ between adjacent pulses is determined by $t_p = L_z/V_g$, where $V_g$ is the velocity of Poynting fluxes, i.e. the group velocity of the interaction point. Since $V_g$ varies at different working voltages, the period of pulses can be tuned by the working voltage.

Then, the growth rates at different trips in the F–P cavity are analyzed. Taking the working voltage $U = 3 \text{kV}$ as an example, the growth rates of Poynting flux in different trips are shown in figure 5. The backward mode SSP is excited firstly as shown in figure 4, and extracts energy from the FEB. The amplitude of Poynting flux increases towards to the left end due to the beam-wave interaction. When the Poynting flux arrives the left mirror, it is partly reflected and propagates forwardly. The amplitude of Poynting flux remains steady because of

![Figure 3](image_url)
mismatch between the forward-wave and the FEB. When the Poynting flux arrives at the right mirror, part of the Poynting flux is transmitted, generating a radiation pulse consequently. The rest of the Poynting flux is reflected by the mirror, propagating backwardly and re-engages the beam-wave interaction process. A back-and-forth trip is completed in this way. In the following passes, the variations of the Poynting flux are similar with the first pass. The Poynting flux, which is reflected to the F–P cavity, continues to increase due to the beam-wave interaction. In general, the Poynting flux increases during the backward process, and maintains steady in the forward process. After a long time, the beam-wave interaction reaches a saturation state and net exchange of energy approaches to zero. The amplitude of the Poynting flux reaches a maximum consequently, as shown in figure 4.

2.2.2. Beam-wave interaction in the forward-wave region

When \( U > 4.6 \) kV, the intersection point lies in the forward region. The working current \( I = 400 \) mA. The case without F–P cavity is analyzed firstly. The Poynting flux distribution along the plasmonic grating surface is presented in figure 6. The SSP is excited by the FEB and propagates forwardly along the plasmonic surface. The
Poynting flux increases because of the beam-wave interaction, then reaches a maximum value at the right end of the grating. The time-space power distributions with F–P cavity are depicted in figure 7. Unlike the beam-wave interaction in backward-wave modes, the Poynting flux increases forwardly and hold steady in the backward process. The Poynting fluxes are reflected for multi-pass regenerated amplification in the same way as the backward-wave mode. As shown in the figures 6 and 7, the output power is enhance about two orders of magnitudes at $U = 6.5$ and $7$ kV. The comparison between the conditions with and without F–P cavity proves that regenerated amplification introduced by the F–P cavity is an efficient way to improve the interaction efficiency. Additionally, there may be several Poynting fluxes excited in the beam-wave interaction process, and they cancel out each other with opposite directions. However, the beam-wave interaction is not influenced in spite of the fluctuations.

### 3. Discussion

In generally, there are a series of resonant frequencies in an optical cavity, and the electromagnetic wave which dissatisfies the resonant condition decays. However, the cavity effect is relatively weak in the F–P cavity loaded...
interaction system in this paper. There are several reasons. Firstly, the SSP is excited along the plasmonic surface, and the longitudinal wave vector $k_z$ is far larger than the wave vector $k$ in vacuum. The length of the F–P cavity is 9 mm which is far longer than the waveguide wavelength of interaction frequency. Thus, the F–P cavity cannot be regarded as a cavity for the SSP, and the resonant effect is weak. Secondly, the F–P cavity is placed above the plasmonic grating. The amplitude of the SSP decays along the direction of the positive axis $x$. The F–P cavity has a minimal effect on the electromagnetic wave distribution, which is verified in the frequency spectrum as shown in figure 8. Similarly, optical amplifiers can be divided into two classes: traveling-wave amplifiers and F–P amplifiers [34–36]. For the former, the cavity feedback effect is weak, which is similar with TWTs in VEDs. For the latter, the cavity resonance effect is significant. The signal is effectively trapped inside the F–P cavity and experiences multiple light–matter interaction. The multi-pass amplification mechanism in an optical cavity is rarely applied to VEDs. Due to the similarity between the beam-wave interaction and the light–matter interaction, it is incentive to introduce the multi-pass amplification in VEDs. The mechanism studied in this paper combines the beam-wave interaction with multi-pass amplification, which is a convenient way to extend the equivalent beam-wave interaction length, and it may lead to a bright perspective of THz radiation sources.

The gap $g$ between the F–P cavity and the metallic grating has a great influence on the beam-wave interaction. In order to confine the SSP and to provide feedback for the Poynting flux, the gap has to satisfy the condition: $g < \delta$, where $\delta$ is the decay length of the trapped SSP (which is calculated by $\delta = 2\pi/\tau_n$). If $g > \delta$, the Poynting flux cannot be trapped in the F–P cavity, and the regenerated amplification effect disappears. The Poynting flux distribution with $g = 15 \mu m$ is shown in figure 9, and the Poynting flux is amplified in a single trip. Additionally, the absent of the regenerated amplification mechanism with the large gap proves that the beam-wave interaction is enhanced due to the regenerated amplification instead of the high-Q factor of the F–P cavity.

Compared with the Poynting flux distribution without the F–P cavity, the peak power of the pulsed radiation is enhanced largely and the time period is tunable by adjusting the working voltage. It is promising to drive the dynamic nuclear polarization nuclear magnetic resonance (DNP-NMR), which needs the nanosecond THz power. The F–P cavity loaded grating interaction system extends the interaction length several times and the
interaction efficiency is improved consequently. It is a convenient way to achieve effective interaction via the multi-pass regenerated amplification avoiding a long interaction circuit.

4. Summary

In this paper, the regenerated amplification mechanism is introduced to enhance the beam-wave interaction efficiency in the THz band. Inspired by laser systems, an optical F–P cavity loaded grating is introduced to provide feedback for this beam-wave interaction system. The Poynting flux excited by the FEB experiences regenerated amplification via round-trip interactions within the F–P cavity. The interaction efficiency is considerably enhanced due to such extended multiple interaction paths. Pulsed THz radiation is obtained at the end of the grating, and the period can be controlled by the working voltage. Additionally, the beam-wave interactions in backward-wave and forward-wave modes are analyzed by the PIC simulation. Compared with the interaction without the F–P cavity, the output radiation is enhanced by more than 8 times in backward-wave mode and more than two orders of magnitude in forward-wave mode. This paper provides a robust and efficient way to enhance the efficiency, and it is also applicable for other free-electron-driven THz VEDs. Furthermore, the regenerated amplification of the SSP within the F–P cavity mitigates the conventional challenges of requiring a high rate of FEB transmission in a long rectilinear beam device. It is promising to develop on-chip high efficient THz radiation sources by combining the photonic devices and electric devices.

Acknowledgments

This work is sponsored by the National Natural Science Foundation of China under Contracts 61531002, 61861130367 (Newton Advanced Fellowship NAF\ R1 | 180121), and NSAF U1830201.

References

[1] Siegel P H 2002 IEEE Trans. Microw. Theory Tech. 50 910–28
[2] Tomouchi M 2007 Nat. Photon. 1 97
[3] Koenig S et al 2013 Nat. Photon. 7 977
[4] Siegel P H 2004 IEEE Trans. Microw. Theory Tech. 52 2438–47
[5] Xu W, Xie L, Zhu J, Xu X, Ye Z, Wang C, Ma Y and Ying Y 2016 ACS Photonics 3 2308–14
[6] Ahmadivand A, Gerislioglu B, Tomitaka A, Manickam P, Kaushik A, Bhamasani S, Nair M and Pala N 2018 Biomed. Opt. Express 9 373–86
[7] Park S, Cha S, Shin G and Ahn Y 2017 Biomed. Opt. Express 8 3551–8
[8] Ahmadivand A, Gerislioglu B, Manickam P, Kaushik A, Bhamasani S, Nair M and Pala N 2017 ACS Sensors 2 1359–68
[9] Nanni E A, Barnes A B, Griffin R G and Temkin R J 2011 IEEE Trans. Terahertz Sci. Technol. 1 145–63
[10] Shu G, He W, Zhang L, Yin H, Zhao J, Cross A W and Phelps A D 2016 IEEE Trans. Electron Devices 63 4955–60
[11] He W, Zhang L, Bowes D, Yin H, Ronald K, Phelps A and Cross A 2015 Appl. Phys. Lett. 107 133501
[12] Tuck J C, Basten M A, Gallagher D A and Kreischer K E 2016 Operation of a compact 1.03 THz power amplifier 2016 IEEE Int. (IEEE) Vacuum Electronics Conf. (IVEC), pp 1–2
[13] Glyavin M Y, Luchinin A G and Golubiatnikov G Y 2008 Phys. Rev. Lett. 100 015101
[14] Pendry J, Martin-Moreno I and Garcia-Vidal F 2004 Science 305 847–8
[15] Maier S A, Andrews S R, Martin-Moreno L and Garcia-Vidal F 2006 Phys. Rev. Lett. 97 176805
[16] Liu W and Xu Z 2014 New J. Phys. 16 073008
[17] Kumar G, Li S, Jadidi M M and Murphy T E 2013 New J. Phys. 15 085031
[18] Kumar G, Pandey S, Cui A and Nahata A 2011 New J. Phys. 13 033024
[19] Liu Y Q, Kong L B, Du C H and Liu P K 2016 IEEE Trans. Plasma Sci. 44 930–7
[20] Liu W, Gong S, Zhang Y, Zhou J, Zhang P and Liu S 2012 J. Appl. Phys. 111 063107
[21] Liu Y Q, Du C H and Liu P K 2016 IEEE Trans. Plasma Sci. 44 3288–94
[22] Zhang Y, Zhou Y and Dong L 2013 Opt. Express 21 21951–60
[23] Zhou Y, Zhang Y, Jiang G and Wu Z 2015 J. Phys. D: Appl. Phys. 48 345102
[24] Shin Y M, So K J, Jang K H, Won J H, Srivastava A and Park G S 2007 Phys. Rev. Lett. 99 147402
[25] Zhang Y, Zhou Y, Gang Y, Jiang G and Yang Z 2017 Sci. Rep. 7 41116
[26] Kong L, B, Huang C P, Du C H, Liu P K and Yin X G 2015 Sci. Rep. 5 8772
[27] Liu S, Zhang P, Liu W, Gong S, Zhong R, Zhang Y and Hu M 2012 Phys. Rev. Lett. 109 153902
[28] Liu P, Xiao L, Ye Y, Wang M, Cui K, Feng X, Zhang W and Huang Y 2017 Nat. Photon. 11 289
[29] Zhang K, Li D, Chang K, Zhang K and Li D 1998 Electromagnetic Theory for Microwaves and Optoelectronics (Berlin: Springer)
[30] Zhou J, Liu D, Liao C and Li Z 2009 IEEE Trans. Plasma Sci. 37 2002–11
[31] Rusina A, Durach M and Stockman M 2010 Appl. Phys. A 100 575–8
[32] Orsád M, Long L, Bell R, Bell S, Bell R, Alexander R and Ward C 1983 Appl. Opt. 22 1099–119
[33] Berenger J P 1994 J. Comput. Phys. 114 185–200
[34] Ghafouri-Shiraz H 1996 Fundamentals of Laser Diode Amplifiers (New York: Wiley)
[35] Tredicucci A and Di Carlo A 2009 Nat. Photon. 3 681
[36] Kao T Y, Reno J L and Hu Q 2017 Optica 4 713–6