TERAHERTZ (THz) RADIATION BY HIGH POWER LASER PLASMA INTERACTION

SUBODH KUMAR

CENTRE FOR ENERGY STUDIES

INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2017

TERAHERTZ (THz) RADIATION BY HIGH POWER LASER PLASMA INTERACTION

by

SUBODH KUMAR

Centre for Energy Studies

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

Indian Institute of Technology Delhi

May 2017

To

My Parents

Certificate

This is to certify that the thesis entitled ***"Terahertz (THz) Radiation by High Power Laser Plasma Interaction"*** submitted by *Mr.* ***Subodh Kumar*** to the Indian Institute of Technology Delhi, is worthy of consideration for the award of the degree of ***'Doctor of Philosophy'*** and is a record of bonafide research work carried out by him. The thesis has reached the standards fulfilling the requirement of the regulations relating to the degree. The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma. I approve the thesis for the award of the aforesaid degree.

Dr. R. Uma

Associate Professor

(Co-supervisor)

Centre for Energy Studies

Indian Institute of Technology Delhi

Hauz Khas, New Delhi-110016

New Delhi

Date:

Dr. R. P. Sharma

Professor

(Supervisor)

Centre for Energy Studies

Indian Institute of Technology Delhi

Hauz Khas, New Delhi-110016

New Delhi

Date:

Acknowledgements

I would like to express my deep sense of gratitude to my supervisor, Prof. R. P. Sharma for his invaluable guidance, constant support and encouragement throughout the course of my research work. His immense knowledge in the subject and humanitarian approach has always been a source of inspiration. His joy and enthusiasm for research kept me motivated all the time. I feel fortunate to have him as advisor and mentor for my Ph.D. work. I am proud of my academic roots and hope to pass on the values of research that he imbibed in me.

I would also like to extend my sincere gratitude to Dr. R. Uma for her constructive suggestions and unwavering support. I convey my sincere thanks to Prof. Joby Joseph, Prof. T. S. Bhatti, Dr. Ramesh Narayanan and all faculty members of Centre for Energy Studies, IIT Delhi for their valuable suggestions, advices and approval of my thesis work. I thank other staff members of Center for Energy studies (CES), IIT Delhi for their kind help and cooperation during my research work.

I am thankful to my parent organization, Defence Research and Development Organization (DRDO), Ministry of Defence for allowing me to pursue the research work. I am also thankful to my colleagues and friends at DRDO, Metcalfe House, Delhi, for their constant support and encouragement.

I am particularly thankful to all my group members at CES, Dr. Monika Singh, Dr. Kalpesh modi, Dr. Nitin Yadav, Dr. Nidhi Sharma, Dr. Alok ji, Dr. Nilesh Kumar Pathak, Dr. Ravindra Goel, Sangita, Anju, Ashish, Swati, Dr. Motilal Rinawa, Prachi, Pradeep, Saba, Narender, Gyanendra, Hardik, Richa, Neha and Sintu for their cooperation, and support during my research work. I owe special thanks to Dr. Ram Kishor Singh who not only helped me in conceptualizing research problems but has been a constant support throughout my research work.

Last but not the least, this acknowledgement would not be complete without expressing my sincere feelings towards my parents, my wife, my children and other family members for their patience and understanding during my research work. I thank them from the bottom of my heart for their support in fulfilling my long cherished dream.

Subodh Kumar

Abstract

The thesis deals with the mechanisms of electromagnetic radiation generation in terahertz frequency range by high power laser plasma interaction. The semi analytical approach has been adopted to study the mechanisms of generation.

The terahertz waves can be generated by various ways using the laser plasma interaction. The three main mechanisms of generation under different conditions and laser plasma parameters have been considered in the present thesis. The first mechanism of generation that we have considered is the beat wave mechanism. Two chapters of the thesis describe the studies based on the beat wave mechanism of terahertz generation. One of these chapter deals with terahertz (THz) generation by beating of two co-axial Gaussian laser beams, propagating in pre formed ripple density plasma when both ponderomotive and relativistic nonlinearities are operative. When the two lasers co-propagate in rippled density plasma, electrons acquire a nonlinear velocity at beat frequency in the direction transverse to the direction of propagation. This nonlinear oscillatory velocity couples with the density ripple to generate a nonlinear current which in turn generates THz radiation at the difference frequency. The necessary phase matching condition is provided by the density ripple. Relativistic ponderomotive focusing of the two lasers and its effects on yield of the generated THz amplitude have been discussed. Numerical results show that conversion efficiency of the order of 10^{-3}can be achieved in the terahertz radiation generation with relativistic ponderomotive focusing.

In the other chapter based on the beating mechanism of terahertz generation, the two laser beams have Super-Gaussian profiles. Here, the investigation has been made in presence of an axially applied static magnetic field. Only ponderomotive nonlinearity is considered which arises due to non uniform spatial intensity profiles of laser beams. Frequencies of

lasers are chosen such that the beat frequency lies in the terahertz region. The density ripple provides the phase matching for resonant excitation and the axial static magnetic field is utilized to enhance the nonlinear coupling. Numerical results show that the yield of the generated THz amplitude enhances with increase in index of super-Gaussian lasers as well as the magnitude of the axially applied static magnetic field.

The next mechanism presented in the thesis is the generation by an amplitude modulated Gaussian laser beam propagating in ripple density plasma. A transient transverse current is generated by transverse component of ponderomotive force exerted by laser on electrons that drives radiation at the modulation frequency (which is chosen to be in the THz domain) because of the variation in intensity in the direction transverse to the laser propagation. The transient focusing of laser beam and its effect on the generated terahertz amplitude has also been studied.

The rest three chapters of the thesis are dedicated to the investigations of terahertz generation by the third mechanism- optical rectification. We have investigated THz generation mechanism by a Gaussian laser pulse (Gaussian in space and time) having pulse duration of order of hundreds of femtosecond and propagating in ripple density plasma. The laser pulse is considered to be intense enough to impart electrons velocities in the relativistic range. Owing to the variation in intensity in the direction transverse to the direction of propagation, a component of ponderomotive force is exerted on electrons, which imparts oscillatory velocity to the electrons. The frequency of this oscillatory velocity falls in THz region if the pulsewidth of the laser is chosen suitably. The transverse component of this oscillatory velocity couples to the density ripple that results in a transient current, driving the THz radiation. Effects of relativistic self focusing on the generated THz amplitude are also discussed in the chapter. We have extended the investigation and studied the THz generation in presence of an externally applied axial magnetic field. Effect of the axial magnetic field on the generated THz intensity has been investigated. Variations in THz radiation intensity as functions of the density ripple amplitude and background plasma density have also been studied.

The study of terahertz generation by optical rectification process has been extended further by replacing the Gaussian profile laser by a laser beam having spatially super Gaussian and temporally Gaussian intensity profile. The quasi-static ponderomotive force which is generated due to the variation in intensity of laser pulse leads to a non linear current density in the direction transverse to the direction of propagation which drives a radiation. The frequency of this radiation falls in THz range if the pulse duration of the laser is chosen suitably. The density ripple provides the phase matching. The yield of generated THz have been compared when the phase matching is exact and that when there is slight mismatch of phases. The variation in the intensity of the generated THz with the index of super Gaussian pulse has also been studied.

सारांश

यह शोध प्रबंध लेज़र प्लाज्मा इंटरैक्शन द्वारा टेराहर्टज़ आवृति की तरंगो की उत्पत्ति की प्रक्रिया को दर्शाता है । इस शोध प्रबंध में अर्ध विश्लेषणात्मक पद्धति को अपनाया गया है ।

लेज़र प्लाज्मा इंटरेक्शन का उपयोग करके कई तरीकों से टेराहर्टज़ आवृति की तरंगो की उत्पत्ति की जा सकती है । इस शोध प्रबंध में मुख्य्तः तीन विधियों का उपयोग लेज़र प्लाज्मा के विभिन्न पैरामीटर्स के लिए किया गया है । पहली विधि दो लेज़र की किरणों की आवृत्तियों के बीटिंग द्वारा टेराहर्टज़ तरंगो की उत्पत्ति पर आधारित है । इस शोध प्रबंध के दो अध्याय इसी विधि पर आधारित है । इनमे से एक अध्याय में दो गॉसियन लेज़र किरणों द्वारा रिलेटिविस्टिक पोंडेरोमोटिव नॉनलीनियरिटी की उपस्थिति में टेराहर्टज़ आवृति की तरंगो की उत्पत्ति की दिखाई गयी है । जब दो लेज़र किरणे प्लाज्मा माध्यम में साथ-साथ चलती हैं तो इलेक्ट्रॉन्स पर पोंडेरोमोटिव बल लगता है जिसकी आवृत्ति दोनों लेज़र किरणों की आवृत्तियों के अंतर के बराबर होती है । यह आवृत्ति टेराहर्टज़ के बराबर होगी अगर लेज़र किरणों के आवृत्तियों का चुनाव उचित हो । यह बल इलेक्ट्रॉन्स को नॉनलीनियर वेग प्रदान करता है जो डेंसिटी रिप्पल के साथ युग्मित होकर नॉनलीनियर करेंट डेंसिटी की उत्पत्ति करता है । यही नॉनलीनियर करेंट डेंसिटी टेराहर्टज़ आवृति की तरंगो की उत्पत्ति के लिए ज़िम्मेदार होता है । फेज़ मैचिंग की पूर्ती डेंसिटी रिप्पल के द्वारा होती है । इस अध्याय में टेराहर्टज़ आवृति की तरंगो की इंटेंसिटी पर सेल फोकसिंग के प्रभाव का भी अध्ययन किया गया है । इस विधि द्वारा संपरिवर्तन की दक्षता $१०^{-३}$ तक प्राप्त किया जा सकता है ।

लेज़र की किरणों की आवृत्तियों के बीटिंग विधि पर आधारित दूसरे अध्याय में गॉसियन की जगह सुपर गॉसियन लेज़र तरंगों का उपयोग किया गया है। साथ ही लेज़र किरणों की प्रसार की दिशा

में एक स्थिर मैग्नेटिक फील्ड का प्रयोग किया गया है जो की टेराहर्टज़ की इंटेंसिटी को बढ़ाने का काम करता है। इस अध्ययन में सिर्फ पोंडेरोमोटिव नॉनलीनियरिटी पर विचार किया गया है। इस अध्ययन में यह पाया गया की सुपर गॉसियन इंडेक्स की वृद्धि करने से टेराहर्टज़ की इंटेंसिटी में बढ़ोत्तरी होती है।

शोध प्रबंध में टेराहर्टज़ उत्पत्ति के लिए एम्पलीच्यूड मॉडुलेटेड लेज़र किरणों का उपयोग दूसरी तकनीक है जिसका इस्तेमाल किया गया है। इनमे भी सिर्फ पोंडेरोमोटिव नॉनलीनियरिटी का उपयोग किया गया है। इलेक्ट्रॉन्स पर लग रहे पोंडेरोमोटिव बल की वजह से ट्रांस्वर्स दिशा में एक ट्रांसिएंट करेंट की उत्पत्ति होती है जो इलेक्ट्रोमैग्नेटिक तरंगों की उत्पत्ति के लिए ज़िम्मेदार होता है। उत्पन्न तरंग की आवृत्ति टेराहर्टज़ होगी यदि मॉडुलेशन की आवृत्ति टेराहर्टज़ की सीमा में हो।

बाकी के तीन अध्याय उच्च शक्ति के लेज़र के ऑप्टिकल रेक्टिफिकेशन पर आधारित है । एक अध्याय में फेम्टोसेकन्ड लेज़र के ऑप्टिकल रेक्टिफिकेशन द्वारा रिलेटिविस्टिक पोंडेरोमोटिव नॉनलीनियरिटी की उपस्थिति में टेराहर्टज़ की उत्पत्ति की पड़ताल की गयी है । इस अध्याय में टेराहर्टज़ इंटेंसिटी पर लेज़र की सेल्फ फोकसिंग के प्रभाव का अध्ययन भी किया गया है । आगे के अध्यायों में इसका विस्तार किया गया है और गॉसियन की जगह सुपर गॉसियन लेज़र पल्स का उपयोग किया गया है । इन अध्यायों में यह दिखाया गया है की लेज़र प्लाज्मा के विभिन्न पैरामीटर्स का उपयोग कर टेराहर्टज़ तरंगों की उत्पत्ति की जा सकती है अगर लेज़र के पल्सविड्थ का चुनाव पूर्वनियोजित तरीके से किया गया हो । इन अध्यायों में फेज मिसमैच फैक्टर पर भी विचार किया गया है और उन परिस्थितियों में उत्पन्न टेराहर्टज़ इन्टेन्सिटीज़ का तुलनात्मक अध्ययन भी किया गया है जब फेज मैचिंग पूर्ण हो और जब फेज मैचिंग में थोड़ा मिसमैच हो । टेराहर्टज़ पर बाहय स्थैतिक मैग्नेटिक फील्ड के प्रभाव का भी अध्ययन किया गया है.

Contents

List of Figures