

**MICROSTRUCTURED FIBERS AND NONLINEAR  
CRYSTALS BASED TERAHERTZ SOURCES AND  
DEVICES**

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# **Microstructured Fibers and Nonlinear Crystals based Terahertz Sources and Devices**

*by*

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Submitted

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*Dedicated To*  
*Lord Shiva, Goddess Saraswati*  
*My Parents*  
*Shri Devender Kumar & Smt. Rukmani Devi,*  
*My Sister Priyanka,*  
*My Ph.D. Supervisors*

## Certificate

This is to certify that the proposed thesis entitled *Microstructured Fibers and Nonlinear Crystals based Terahertz Sources and Devices* being submitted by **Mr. Vikas Kumar** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried by him. He has worked under our guidance and supervision and has fulfilled the requirements which to our knowledge and has reached the requisite standard for the submission of the thesis. The results contained in the thesis have not been submitted in part or full to any University or Institute for the award of any degree or diploma.

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## Abstract

Terahertz (THz) waves spanning a frequency range of 0.1 to 10 THz, typically, lie midway between microwaves and infrared waves in the broad electromagnetic spectrum. Many scientific and technological applications like imaging, sensing, spectroscopy, communication, etc. have emerged in the THz regime by continuous research and development in last few decades. Researchers are trying to design high power THz sources, THz linear and nonlinear devices, THz beam modulators, etc. In this thesis, we have studied theoretically, various designs of photonic crystal fibers (PCFs) and microstructured fibers for applications as efficient sources, compact devices for polarization splitting, wave modulation, and sensors for THz radiation.

Varieties of linear characteristics like single-mode operation and near-zero dispersion guiding, large modal area, high birefringence, high numerical aperture, and low loss have been accomplished and demonstrated by designing suitable PCF structures. The microstructured configuration in a variant of teflon host possesses a combination of near core teflon inclusions and air holes in the first ring around the central core provides flexibility for acquiring desirable dispersion characteristics and suitability for high power propagation. Broadband THz propagation with nearly flat (near to zero) dispersion in the spectral range of  $\sim 153\text{-}221\ \mu\text{m}$  ( $\sim 1.35\text{-}1.96\ \text{THz}$ ) and bandwidth of  $\sim 78\ \mu\text{m}$  ( $0.61\ \text{THz}$ ) is demonstrated using optimized photonic band gap (PBG) fiber. The designed polyethylene (PE) photonic crystal index guided fiber (PCIGF) offers the minimum dispersion values ( $\sim 0.05\ \text{dB/m}\cdot\mu\text{m}$ ) around 1 THz at which, flat mode and high power propagation due to large modal area of are also achieved. Further, we have designed alternatively air-holes and material-inclusions rings around the single core teflon PCIGF to achieve THz supercontinuum with spectral range of  $160\text{-}270\ \mu\text{m}$  ( $\sim 1.1\text{-}1.878\ \text{THz}$ ) and bandwidth of  $110\ \mu\text{m}$  ( $\sim 0.8\ \text{THz}$ ). Beyond the reported complicated and fragile structures in the literature, the polymer based PCFs are relatively simple and can be fabricated by using the standard stack and draw method.

Polarization selective applications, instruments, and measurements have recently attracted attention for development. We observed an excellent potential for efficient polarization splitting using dual-core PCIGF which can be used to realize compact, very efficient, and low loss polarization splitter. We implemented two configurations in the dual-core PCIGF to lower the splitting length of the fiber, have high extinction ratio and low propagation and bending losses. In the first scheme, we have proposed a suitable configuration of the gradient in various pitches for air holes lattice in the two cores of polyethylene PCIGF, to reduce the splitting

length of 60 cm compared to the previously reported design by two orders and high extinction ratios i.e. 18 dB for  $y$ -polarization and 23 dB for  $x$ -polarization. Selective inclusion of teflon rods in the air holes configuration of both the cores further reduces the splitting length i.e.  $\sim 2.1$ cm to 20cm at 0.4 to 1 THz frequencies, correspondingly. The extinction ratios for the  $x$ - and  $y$ -polarization have been found to be 70 dB and 40 dB, respectively which are very high. The confinement, propagation, and bending loss were found to be very low.

We have also ideated a conventional PCF to modify its basis and innermost ring unit cells. It can sense toxic CS<sub>2</sub> by using the supported two modes. The existing limitation of CS<sub>2</sub> sensing is the absence of fingerprint spectral features in the THz frequency range. It has been mitigated by utilizing the time delay difference and differential loss of second-order mode-based criteria on the addition of the CS<sub>2</sub> sensing material in the prescribed holes in the design. Thus, applying the Maxwell Garnett theory, we were able to monitor the concentration of CS<sub>2</sub> under ambient conditions by finding the complex effective permittivity of the second mode for each CS<sub>2</sub> concentration in the prescribed air holes and then analyzing either the time delay difference between the two supported modes as the pulse forms or the second order propagation loss. For a 10 cm long variant of the designed PCF operating at 0.75 THz frequency, we observe a linearly increasing TDD variation from  $\sim 2$  to 13 ps due to change in CS<sub>2</sub> concentration from 17 to 50%. However, when the CS<sub>2</sub> concentration exceeds the 50% range, we observe decreasing TDD characteristics. In this high concentration regime ( $>50\%$ ), we monitor CS<sub>2</sub> by analyzing second mode loss (SML) variation due to concentration change (at 0.98 THz frequency), where SML increases upto  $\sim 30$  dB for  $\sim 100\%$  ambient CS<sub>2</sub> concentration. Here, we achieve a high concentration sensitivity where a variation of 1.6 dB SML is observed with unit concentration change of CS<sub>2</sub>.

Specialty microstructured fibers with customized transverse cross-section help realize an efficient source of THz radiation at  $\sim 9$ THz, which is highly suitable to fingerprint detection of neurotransmitters. We have considered three varieties of Teflon as either host material or rod-like inclusions together with TiO<sub>2</sub> doped polyethylene inclusions in the Teflon host for such fiber designs in our next study presented in the thesis. Teflon has a very high nonlinear coefficient (third-order nonlinearity) that helps to achieve efficient four-wave mixing inside the fiber. We have considered a fiber framework with teflon-1 as the cladding and teflon-2 as the core, within which a hexagonal lattice is embedded in the form of five alternate rings made of teflon-3 and TiO<sub>2</sub> doped polyethylene as inclusions for high power THz generation by four-wave mixing. The pump at 10.56  $\mu\text{m}$  can be taken from a CO<sub>2</sub> laser, while input idler at variable

wavelength ( $\sim 6.2\text{-}6.5\ \mu\text{m}$ ) can be taken from a CO laser. THz frequency tunable output in the range of  $\sim 9.1\text{-}9.33\ \text{THz}$  has been achieved by varying the pump power from 1 kW to 9 kW. We have observed large mode area and high modal overlap among the infrared input pump, infrared seed idler, and output THz waves. THz generation efficiency up to 13% at the optimized coherence length of  $\sim 6.7\ \text{m}$  was possible.

Nonlinear crystals such as ZnTe and LiNbO<sub>3</sub> are among the most popular materials considered for generation of THz radiation by optical rectification of ultrashort NIR pulses in them. In the last study for the present thesis work, we have demonstrated broadband ( $\sim 0.1\text{-}4\ \text{THz}$ ) beam shaping and steering during THz generation by optical rectification of NIR pulses in an electrically controlled  $\chi^{(2)}$ -modulated nonlinear crystal. We have considered different duty cycles of the periodic  $\chi^{(2)}$ -modulations in the crystal transverse to the direction of excitation beam propagation to achieve control on the beam shaping and steering. A maximum angular steering of about  $7.43^\circ$  relative to the undeflected THz beam from otherwise a uniform  $\chi^{(2)}$  nonlinear crystal has been demonstrated in a 1 mm thick ZnTe crystal having modulation period of 0.1 cm such that 2 or more periods are present within the width of the crystal.

The aforementioned studies have the potential to boost the contemporary THz photonics domain where the proposed linear and nonlinear configurations can facilitate a range of fascinating device applications viz. high power THz generation, broadband beam shaping and steering, polarization splitting, and chemical sensing.

## सार

टेराहर्ट्ज़ (THz) तरंगों 0.1 से 10 THz की आवृत्ति रेंज में फैली हुई हैं, आमतौर पर, व्यापक विद्युत चुम्बकीय स्पेक्ट्रम में माइक्रोवेव और अवरक्त तरंगों के बीच में होती हैं। पिछले कुछ दशकों में निरंतर टेराहर्ट्ज़ अनुसंधान और विकास द्वारा कई वैज्ञानिक और तकनीकी अनुप्रयोग जैसे इमेजिंग, सेंसिंग, स्पेक्ट्रोस्कोपी, संचार, आदि उभरे हैं। शोधकर्ता उच्च शक्ति वाले टेराहर्ट्ज़ स्रोतों, टेराहर्ट्ज़ रैखिक और गैर-रेखीय उपकरणों, टेराहर्ट्ज़ बीम मॉड्युलेटर आदि को डिजाइन करने का प्रयास कर रहे हैं। इस थीसिस में, हमने सैद्धांतिक रूप से, कुशल स्रोतों ध्रुवीकरण विभाजन के लिए उपकरण, तरंग मॉडुलन, विकिरण के लिए टेराहर्ट्ज़ सेंसर के रूप में अनुप्रयोगों के लिए फोटोनिक क्रिस्टल फाइबर (PCFs) और माइक्रोस्ट्रक्चर फाइबर के विभिन्न डिजाइनों का अध्ययन किया है।

सिंगल-मोड ऑपरेशन और लगभग-शून्य परिक्षेपण तरंग परिवहन, बड़े मोडल क्षेत्र, उच्च द्विअपवर्तन, उच्च संख्यात्मक एपर्चर, और कम नुकसान जैसी रैखिक विशेषताओं की किस्मों को पूरा किया गया है और उपयुक्त पीसीएफ संरचनाओं को डिजाइन करके प्रदर्शित किया गया है। टेप्लॉन होस्ट के एक प्रकार में माइक्रोस्ट्रक्चर्ड कॉन्फिगरेशन में केंद्रीय कोर के चारों ओर पहली रिंग में निकट कोर टेप्लॉन समावेशन और वायु छिद्रों का संयोजन होता है, जो वांछनीय फैलाव विशेषताओं और उच्च शक्ति प्रसार के लिए उपयुक्तता प्राप्त करने के लिए लचीलापन प्रदान करता है।  $\sim 153\text{-}221 \mu\text{m}$  ( $\sim 1.35\text{-}1.96 \text{ THz}$ ) की स्पेक्ट्रल रेंज में लगभग प्लैट (शून्य के करीब परिक्षेपण के साथ ब्रॉडबैंड टेराहर्ट्ज़ प्रसार  $\sim 78 \mu\text{m}$  ( $0.61 \text{ THz}$ ) की बैंडविड्थ को अनुकूलित फोटोनिक बैंड गैप (PBG) फाइबर का उपयोग करके प्रदर्शित किया जाता है। डिजाइन किया गया पॉलीइथाइलीन (पीई) फोटोनिक क्रिस्टल इंडेक्स गाइडेड फाइबर (PCIGF) 1 THz आवृत्ति के पास न्यूनतम परिक्षेपण मान ( $\sim 0.05 \text{ dB/m-}\mu\text{m}$ ) प्रदान करता है, जिस पर, बड़े मोडल क्षेत्र के कारण प्लैट मोड और उच्च शक्ति प्रसार भी हासिल किया जाता है। इसके अलावा, हमने  $160\text{-}270\mu\text{m}$  ( $\sim 1.1\text{-}1.878 \text{ THz}$ ) की स्पेक्ट्रल रेंज और 110 माइक्रोन ( $\sim 0.8\text{THz}$ ) की बैंडविड्थ के साथ THz सुपरकॉन्टिनम प्राप्त करने के लिए सिंगल कोर टेप्लॉन पीसीआईजीएफ के चारों ओर वैकल्पिक रूप से एयर-होल और सामग्री-समावेश के छल्ले डिजाइन किए हैं। साहित्य में रिपोर्ट की गई जटिल और नाजुक संरचनाओं से परे, बहुलक आधारित पीसीएफ अपेक्षाकृत सरल हैं और मानक स्टैक और ड्रा विधि का उपयोग करके गढ़े जा सकते हैं।

ध्रुवीकरण चयनात्मक अनुप्रयोगों, उपकरणों और मापों ने हाल ही में विकास के लिए ध्यान आकर्षित किया है। हमने दोहरे कोर PCIGF का उपयोग करके कुशल ध्रुवीकरण विभाजन के लिए एक उत्कृष्ट क्षमता देखी, जिसका उपयोग कॉम्पैक्ट, बहुत कुशल और कम नुकसान वाले ध्रुवीकरण स्प्लिटर को

महसूस करने के लिए किया जा सकता है। हमने फाइबर की विभाजन लंबाई को कम करने के लिए दोहरे कोर पीसीआईजीएफ में दो कॉन्फिगरेशन लागू किए, उच्च विलुप्त होने का अनुपात और कम प्रसार और झुकने वाले नुकसान हैं। पहली योजना में, हमने पॉलीइथाइलीन पीसीआईजीएफ के दो कोर में एयर होल जाली के लिए विभिन्न पिचों में ढाल के उपयुक्त विन्यास का प्रस्ताव दिया है, ताकि दो ऑर्डर द्वारा पहले की रिपोर्ट की गई डिजाइन की तुलना में 60 सेमी की विभाजन लंबाई को कम किया जा सके और उच्च विलुप्त होने के अनुपात यानी  $y$ - ध्रुवीकरण के लिए 18 डीबी और  $x$ - ध्रुवीकरण के लिए 23 डीबी प्राप्त किया जा सके। दोनों कोर के एयर होल कॉन्फिगरेशन में टेपलॉन रॉड्स के चुनिंदा समावेश से विभाजन की लंबाई कम हो जाती है यानी  $\sim 0.4$  से 1 THz आवृत्तियों पर 2.1 सेमी से 20 सेमी, तदनुसार  $x$ - और  $y$ - ध्रुवीकरण के लिए विलुप्त होने का अनुपात क्रमशः 70 dB और 40 dB पाया गया है, जो बहुत अधिक है। कारावास, प्रसार और झुकने की हानि बहुत कम पाई गई।

हमने इसके आधार और अंतरतम रिंग यूनिट कक्ष को संशोधित करने के लिए एक पारंपरिक पीसीएफ की भी कल्पना की है। यह समर्थित दो मोड का उपयोग करके विषाक्त  $CS_2$  को महसूस कर सकता है।  $CS_2$  सेंसिंग की मौजूदा सीमा टेराहर्ट्ज़ आवृत्ति रेंज में फ़िंगरप्रिंट वर्णक्रमीय विशेषताओं का अभाव है। डिजाइन में निर्धारित छिद्रों में  $CS_2$  सेंसिंग सामग्री को जोड़ने पर समय विलंब अंतर और दूसरे क्रम मोड-आधारित मानदंड के अंतर हानि का उपयोग करके इसे खत्म किया गया है। इस प्रकार, मैक्सवेल गार्नेट सिद्धांत को लागू करते हुए, हम निर्धारित हवा के छिद्रों में प्रत्येक  $CS_2$  एकाग्रता के लिए जटिल प्रभावी पारगम्यता का पता लगाकर परिवेशी परिस्थितियों में की  $CS_2$  एकाग्रता की निगरानी करने में सक्षम थे क्यों कि या तो समय की देरी के अंतर का विश्लेषण कर रहे थे या स्पंद रूपों के हानि के रूप में दो समर्थित मोड का विश्लेषण। 0.75 THz आवृत्ति पर संचालित डिजाइन किए गए PCF के 10 सेमी लंबे संस्करण के लिए, हम  $CS_2$  एकाग्रता में 17 से 50% तक परिवर्तन के कारण  $\sim 2$  से 13 ps तक रैखिक रूप से बढ़ते TDD भिन्नता का निरीक्षण करते हैं। हालाँकि, जब  $CS_2$  की सांद्रता 50% सीमा से अधिक हो जाती है, तो हम TDD विशेषताओं को कम करते हुए देखते हैं। इस उच्च सांद्रता शासन ( $> 50\%$ ) में, हम  $CS_2$  एकाग्रता परिवर्तन (0.98 THz आवृत्ति पर) के कारण दूसरे मोड हानि (LMS) भिन्नता का विश्लेषण करके की निगरानी करते हैं, जहां LMS  $\sim 100\%$  परिवेश  $CS_2$  एकाग्रता के लिए  $\sim 30$  डीबी तक बढ़ जाता है। यहां, हम एक उच्च सांद्रता संवेदनशीलता प्राप्त करते हैं जहां  $CS_2$  की इकाई एकाग्रता परिवर्तन के साथ 1.6 डीबी MLS की भिन्नता देखी जाती है।

अनुकूलित अनुप्रस्थ क्रॉस-सेक्शन के साथ विशेष सूक्ष्म संरचित फाइबर  $\sim 9$ THz विकिरण के एक कुशल स्रोत का एहसास करने में मदद करते हैं, जो यूरोट्रांसमीटर के फ़िंगरप्रिंट का पता लगाने के लिए अत्यधिक उपयुक्त है। थिसिस में प्रस्तुत हमारे अगले अध्ययन में हमने टेपलॉन की तीन किस्मों को या तो

मेजबान सामग्री या रॉड-जैसे समावेशन के साथ-साथ टेफ्लॉन होस्ट में टीआईओ 2 डोपेड पॉलीइथाइलीन समावेशन के रूप में माना है। टेफ्लॉन में एक बहुत ही उच्च गैर-रेखीय गुणांक (तीसरे क्रम की गैर-रेखीयता) है जो फाइबर के अंदर कुशल चार-लहर मिश्रण प्राप्त करने में मदद करता है। हमने टेफ्लॉन -1 के साथ एक फाइबर फ्रेमवर्क को क्लैडिंग और टेफ्लॉन -2 को कोर के रूप में माना है, जिसके भीतर एक हेक्सागोनल जाली टेफ्लॉन -3 और टीआईओ 2 डोपेड पॉलीइथाइलीन से बने पांच वैकल्पिक रिंगों के रूप में चार-लहर मिश्रण द्वारा उच्च शक्ति के लिए समावेशन के रूप में एम्बेडेड है। 10.56  $\mu\text{m}$  पर पंप को  $\text{CO}_2$  लेजर से लिया जा सकता है, जबकि परिवर्तनीय तरंगदैर्घ्य ( $\sim 6.2\text{--}6.5 \mu\text{m}$ ) इनपुट  $\text{CO}$  लेजर से लिया जा सकता है।  $\sim 9.1\text{--}9.33 \text{ THz}$  की रेंज में  $\text{THz}$  फ्रीक्वेंसी ट्यून करने योग्य आउटपुट के लिए पंप की शक्ति को 1 kW से 9 kW तक बदलकर प्राप्त किया गया है। हमने इन्फ्रारेड इनपुट पंप, इन्फ्रारेड सीड आइडलर और आउटपुट  $\text{THz}$  तरंगों के बीच बड़े मोड क्षेत्र और उच्च मोडल ओवरलैप को देखा है।  $\sim 6.7$  मीटर की अनुकूलित सुसंगतता लंबाई से 13%  $\text{THz}$  स्रोत की दक्षता संभव थी।

$\text{ZnTe}$  और  $\text{LiNbO}_3$  जैसे गैर-रेखीय क्रिस्टल सबसे लोकप्रिय पदार्थों में से हैं, जिन्हें अल्ट्राशॉर्ट NIR स्पंदन के ऑप्टिकल सुधार द्वारा  $\text{THz}$  विकिरण उत्पन्न करने के लिए माना जाता है। वर्तमान थीसिस कार्य के लिए पिछले अध्ययन में, हमने विद्युत नियंत्रित  $\chi^{(2)}$ -मॉड्युलेटेड नॉनलाइनियर क्रिस्टल में NIR स्पंदन के ऑप्टिकल सुधार द्वारा  $\text{THz}$  स्रोत के दौरान ब्रॉडबैंड ( $\sim 0.1\text{--}4\text{THz}$ ) बीम को आकार देने और स्टीयरिंग का प्रदर्शन किया है। हमने बीम आकार देने और स्टीयरिंग पर नियंत्रण प्राप्त करने के लिए उत्तेजना बीम प्रसार की दिशा में क्रिस्टल अनुप्रस्थ में आवधिक  $\chi^{(2)}$ -मॉड्यूलेशन के विभिन्न कर्तव्य चक्रों पर विचार किया है। अन्यथा एक समान  $\chi^{(2)}$  नॉनलाइनियर क्रिस्टल से अपरिवर्तित  $\text{THz}$  बीम के सापेक्ष लगभग  $7.43^\circ$  की अधिकतम कोणीय स्टीयरिंग को 1 मिमी मोटी  $\text{ZnTe}$  क्रिस्टल में 0.1 सेमी की मॉड्यूलेशन अवधि के साथ प्रदर्शित किया गया है, जैसे कि 2 या अधिक अवधि मौजूद हैं।

उपरोक्त अध्ययनों में समकालीन  $\text{THz}$  फोटोनिक्स डोमेन को बढ़ावा देने की क्षमता है जहां प्रस्तावित रैखिक और गैर-रेखीय विन्यास आकर्षक डिवाइस अनुप्रयोगों की एक श्रृंखला की सुविधा प्रदान कर सकते हैं जैसे कि, उच्च शक्ति  $\text{THz}$  स्रोत, ब्रॉडबैंड बीम आकार देने और स्टीयरिंग, ध्रुवीकरण विभाजन, और रासायनिक संवेदन।

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# List of Abbreviations

ARROW	Anti-Resonance Reflecting Optical Waveguides
CS <sub>2</sub>	Carbon Disulfide
FFET	Fast Field-Effect Transistor
FMI	Fractional Modal Intensity
FSM	Fundamental Space Filling Mode
GaP	Gallium Phosphide
GNLSE	Generalized Nonlinear Schroedinger Equation
ITO	Indium Tin Oxide
LiNbO <sub>3</sub>	Lithium Niobate
NA	Numerical Aperture
PCF	Photonic Crystal Fibers
PCIGF	Photonic Crystal Index Guided Fibers
PBG	Photonic Bandgap Guidance
PMD	Polarization Mode Dispersion
THz	Terahertz
TiO <sub>2</sub>	Titanium Dioxide
TDD	Time Delay Difference
TDS	Time-Domain Spectroscopy
SPAF	Source Power Amplification Factor
SML	Second Mode Loss
ZnTe	Zinc Telluride