一般社団法人 電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
IEICE Technical Report
PEM2014-09 (2014-11)

［依頼講演］　光ファイバ実装電気光学プローブを用いたイオンエンジン内のマイクロ波電界分布計測

都甲 浩芳†

† 日本電信電話株式会社　研究企画部門 〒180-8585 東京都武蔵野市緑町 3-9-11
E-mail:　† togo.hiroyoshi@lab.ntt.co.jp

あらまし　自然界に存在する微弱な電磁波から、大きな出力のマイクロ波まで、さまざまな種類の電磁波を測定するために、「金属プローブ」が広く用いられています。従来のプローブは金属で構成されていることから、測定対象から放射された電磁波を散乱し、測定目的の電磁波を正確に捉えられないという問題がありました。NTT では、この問題を改善するため、金属ではなく、通信などで広く利用されている「光ファイバ」を活用した EO プローブを開発しています。また、JAXA では、かねてより小惑星探査機に搭載されるイオンエンジンの研究・開発を進めており、推進性能向上を図ってきました。このイオンエンジンの性能向上を図るため、イオンエンジン作動中にプラズマ中におけるマイクロ波電界の分布を測定する技術を必要としていました。しかし、従来のプローブは、金属を使用しているため電界に散乱を起こしてしまい、また、大型のため精密測定ができず、イオンエンジン内部のプラズマ中のマイクロ波電界について、正確な計測が困難でした。そこで、NTT が開発した「光ファイバ」を活用した EO プローブの低擾乱性（電界の散乱が発生しにくくなる特性）や高空間分解能（空間的に細かい電界分布を測定可能な特性）に注目し、イオンエンジン内のマイクロ波電界の計測に向けて、共同研究を行ってきました。NTT は JAXA との共同研究においてマイクロ波電界の測定に必要とされる感度安定性、耐磁界性、および耐熱性の高い「光ファイバ」を活用した EO プローブを開発し、イオンエンジン内のマイクロ波電界測定に世界で初めて成功しました。測定結果から、マイクロ波が伝搬できなくなるマイクロ波カットオフ現象を緩和することで、イオンエンジンの性能をさらに向上できることが判明しました。今後、マイクロ波放電式イオンエンジンの研究・開発を推し進めることで、イオンエンジンを使用する小惑星探査機がより遠くの惑星への到達することが可能となったり、人工衛星などの宇宙機の長寿命化、等の実現が期待できます。

キーワード　EO プローブ，イオンエンジン，マイクロ波

Fiber-mounted Electro-optic Probe for Microwave Electric-field Measurement in Plasma Environment

Hiroyoshi TOGO†

† Research and Development Planning Department, NTT　3-9-11, Midori-cho, Musashino-shi, Tokyo 180-8585 Japan
E-mail:　† togo.hiroyoshi@lab.ntt.co.jp

Abstract　The demand for greater precision in electric-field measurements is increasing. To meet this demand, NTT Microsystem Integration Laboratories has developed an electro-optic (EO) probe that is mounted on the tip of an optical fiber and has no metal components. This article describes the basic principles and improvements in sensitivity stability and thermal and magnetic resistance of the EO probe. It also presents the results of microwave electric-field measurements conducted in an electron cyclotron resonance ion engine installed on an asteroid explorer under the collaboration of NTT and the Japan Aerospace Exploration Agency.

Keyword　Electro-optic (EO) probe, Optical fiber, Plasma environment

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都甲 浩芳
日本電信電話株式会社　研究企画部門
〒180-8585 東京都武蔵野市緑町3-9-11
E-mail: togo.hiroyoshi@lab.ntt.co.jp

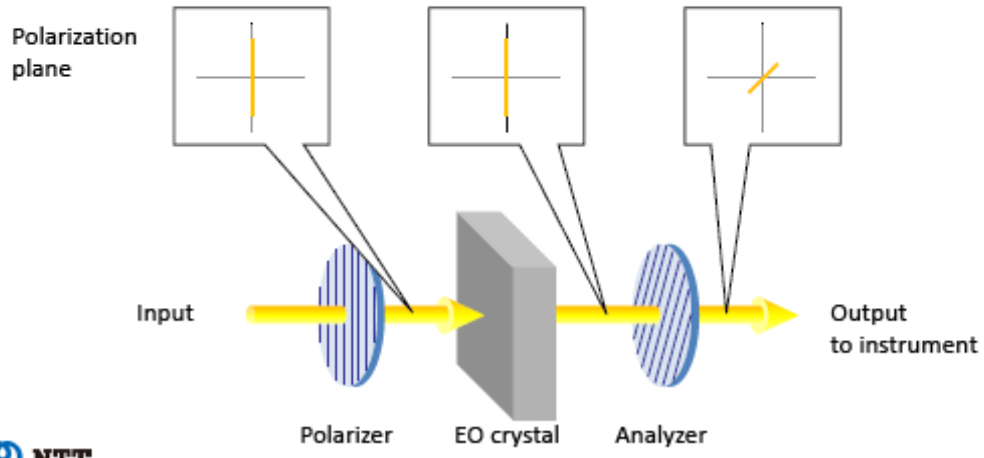
Outline

1. Background
2. Principle of metal-free electric-field probe
3. Probe system and its basic properties
   - Frequency response
   - Sensitivity
   - Directivity
4. EMC applications
   - Inside ion thruster of '*Hayabusa*'
5. Summary

Mechanism of Electric-field Detection

- Linearly polarized light is injected into the electro-optic (EO) crystal, which exhibits Pockels effect.
- When there is no electric field, the light passes through the crystal unchanged.

Without electric field



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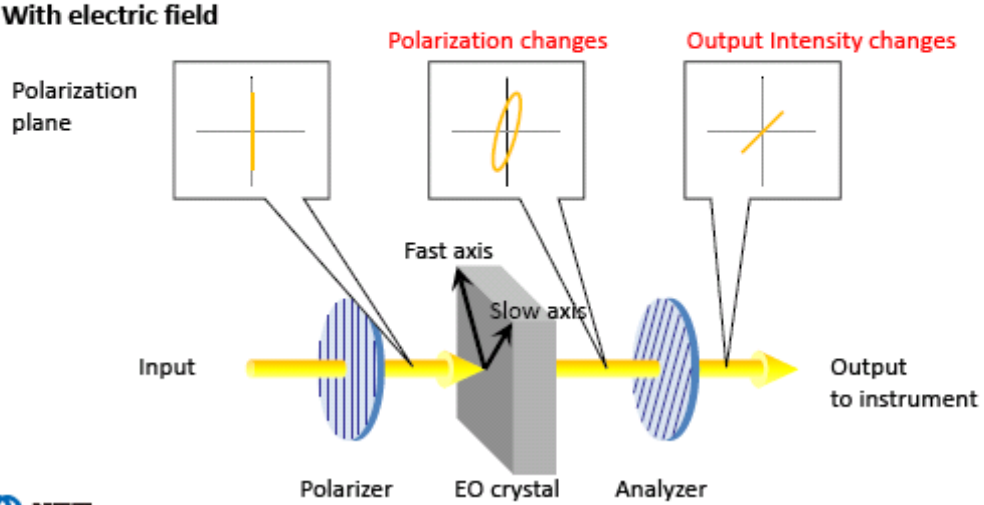
Mechanism of Electric-field Detection

- In the presence of an electric field, the dielectric constant is different on different axes and the linear polarization is converted to elliptic polarization at the EO crystal.
- The output of the polarizer depends on the applied electric field.

With electric field



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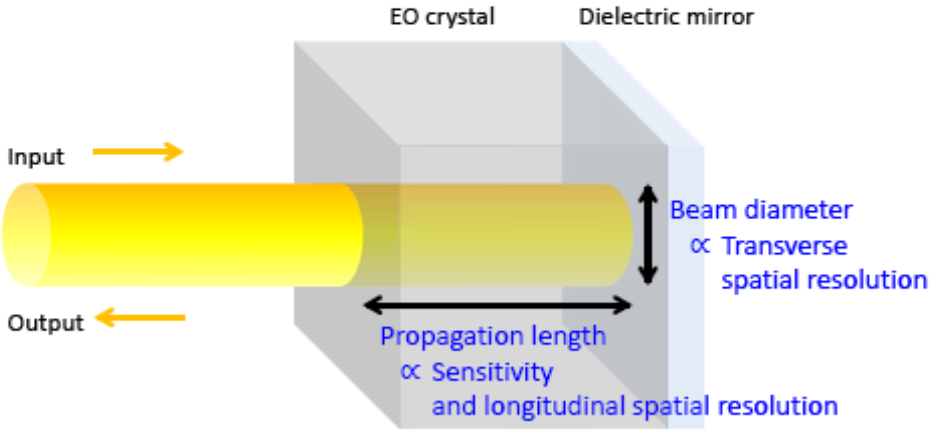
Reflection-type Configuration

- Reflection detection for measurement in small space.
- Propagation length determines sensitivity and longitudinal spatial resolution.
- Beam diameter determines transverse spatial resolution.



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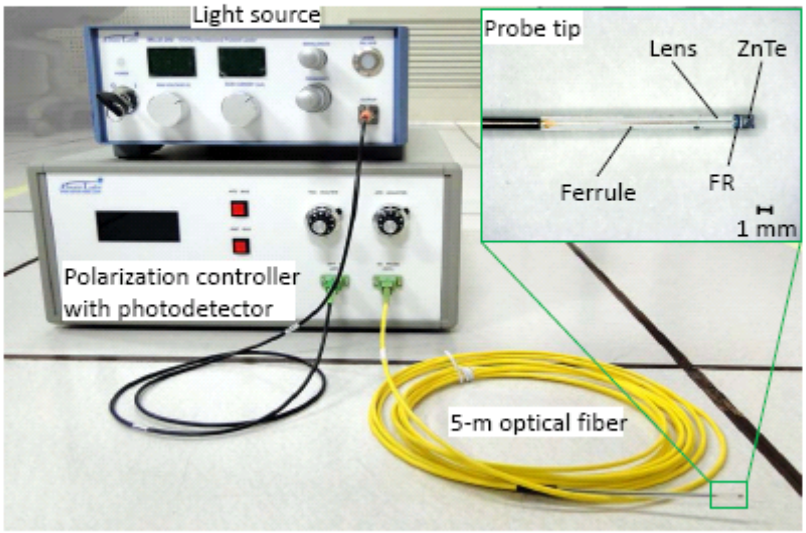
Metal-free Electric-field Probe System

- EO crystal (1 mm on a side) mounted on tip of 5-m-long optical fiber
- Spatial resolution: 0.04 mm (Determined by beam diameter in EO crystal)



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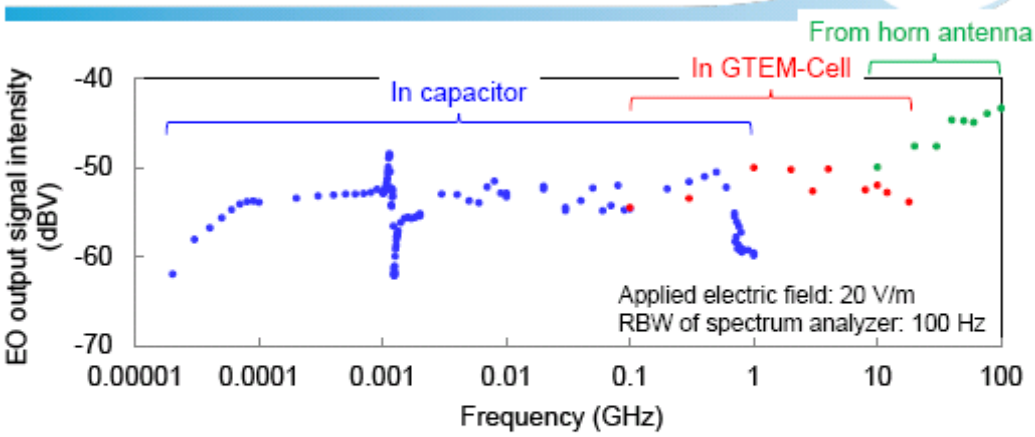
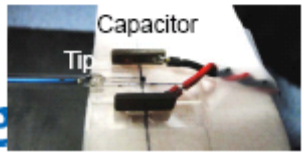
Frequency Response with ZnTe crystal

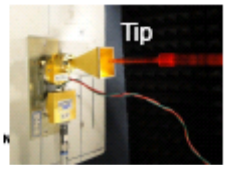


In capacitor
(20 kHz – 1 GHz)



In GTEM-Cell
(0.1 – 18 GHz)

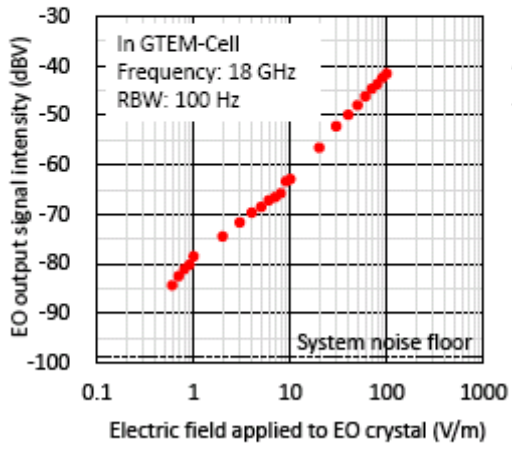
From horn antenna
(10 – 180 GHz)



Sensitivity and Directivity

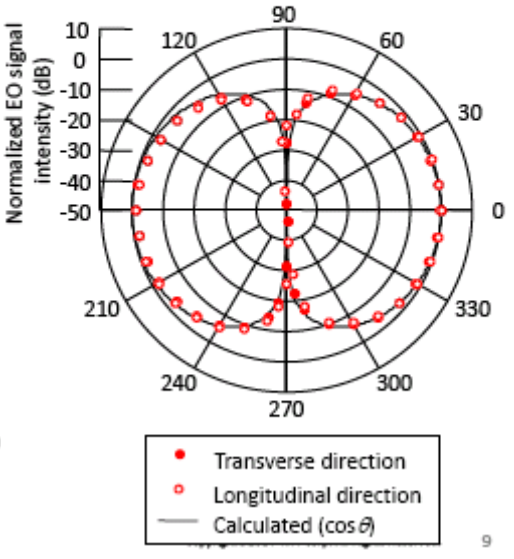
Sensitivity

- Dynamic range: > 90 dB
- Minimum sensitivity: 60 mV/m/√Hz



Directivity

- Polarization discrimination ratio: > 50 dB



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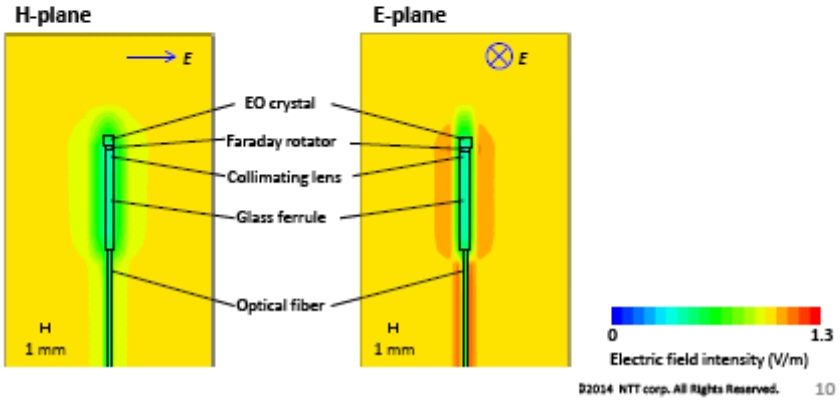
Basic properties with ZnTe Crystal

	Specifications
Components	No metal
Head size	1 mm x 1 mm
Detection direction	Transverse and longitudinal
Frequency range	Several tens kHz - THz
Minimum sensitivity	< 60 mV/m/√Hz

Optimum applications

- Near field
- High voltage
- In ionization
- Detailed measurements
- Remote sensing

etc.



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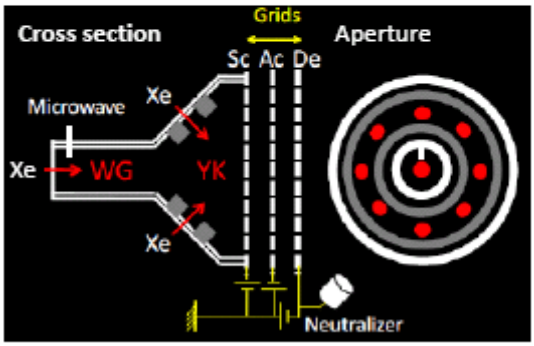
Ion Engine of Spacecraft 'HAYABUSA'

- Asteroid explorer 'HAYABUSA' to acquire samples from the surface of near-Earth asteroid 25143 Itokawa (1998 SF36) and return them to Earth.
- In the next project HAYABUSA-2, we investigated the improvement mechanism of electrical propulsion for the longer travel to asteroid 1999 JU3 with collaboration.

HAYABUSA (Returned in June 2010)

Configuration of ion engine μ10



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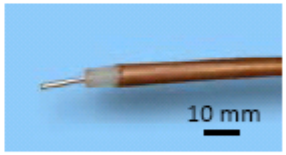
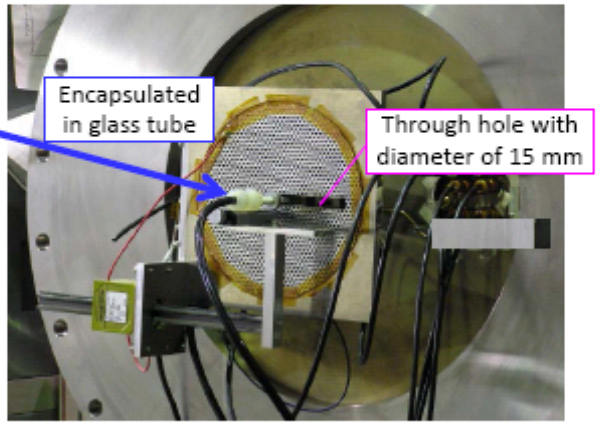
Issues in Conventional Metal Probe

- Disturbance to electric field with a metal probe due to scattering and electrical coupling with grids and waveguide walls inside the ion engine.
- Ionization environment changes due to the modification of grids for insertion of the metal probe with diameter of several millimeter.

Conventional metal probe (Langmuir probe)





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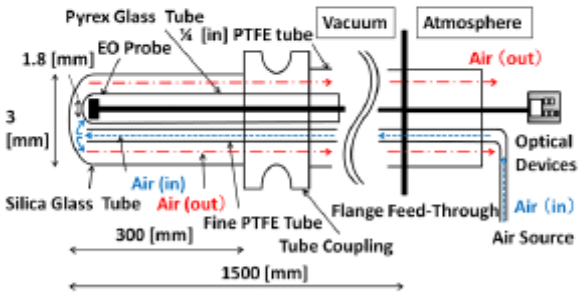
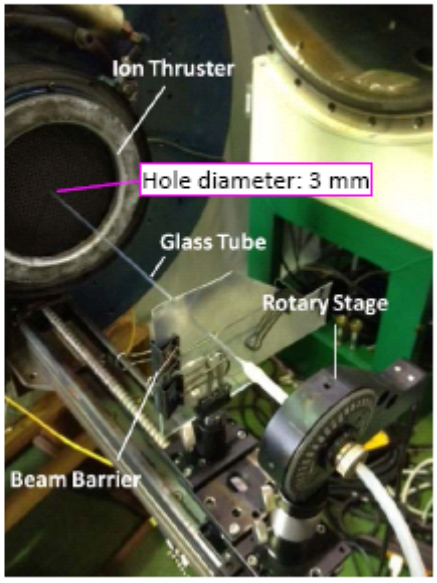
Measurement Setup for Metal-free Probe

- Reduction of the tube diameter to 3 mm.
- Air flow controller for stabilization within the temperature of 25 ± 0.5 ℃.

Probe configuration





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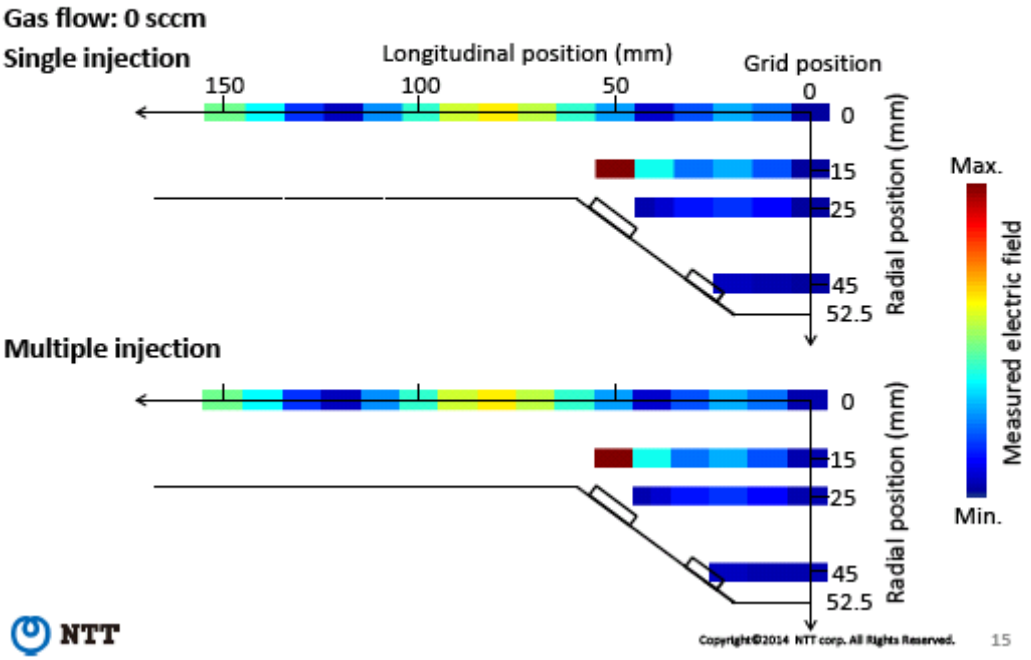
Measured Electric-field Distribution



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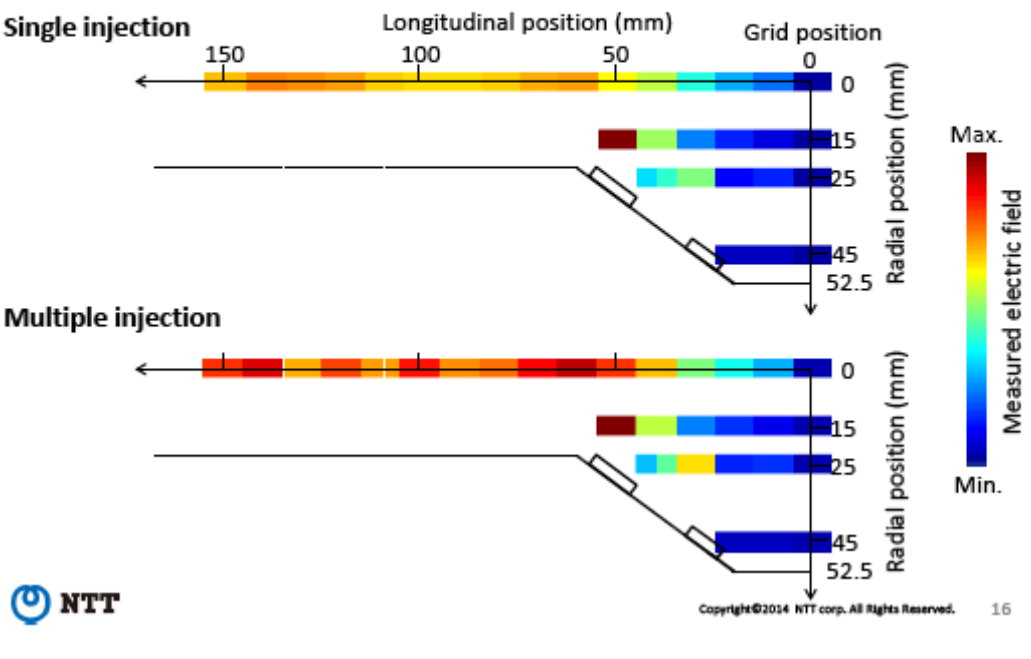
Measured Electric-field Distribution



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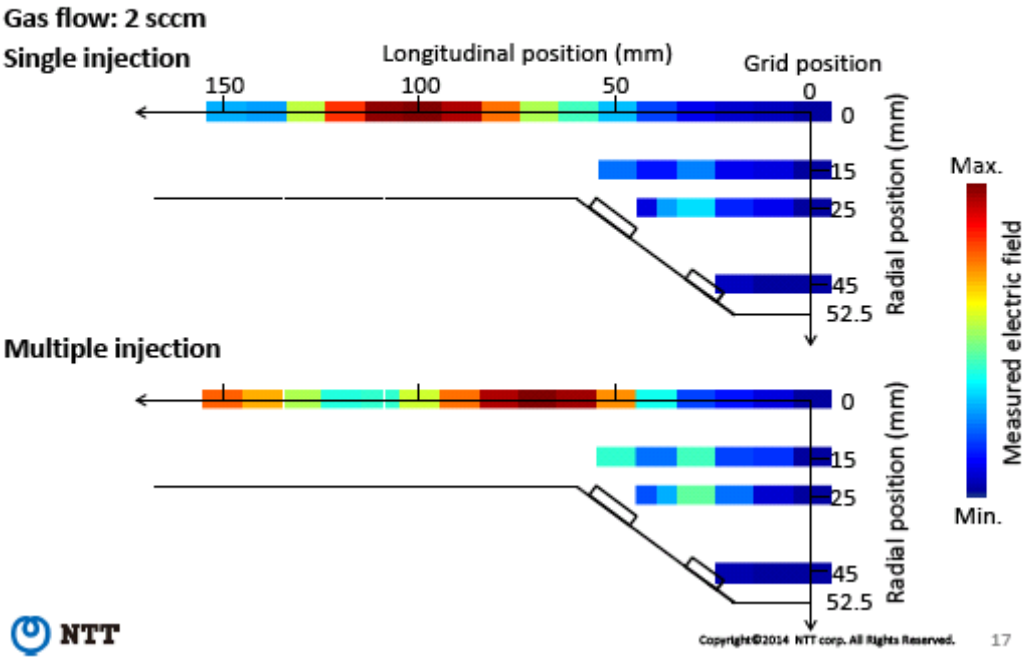
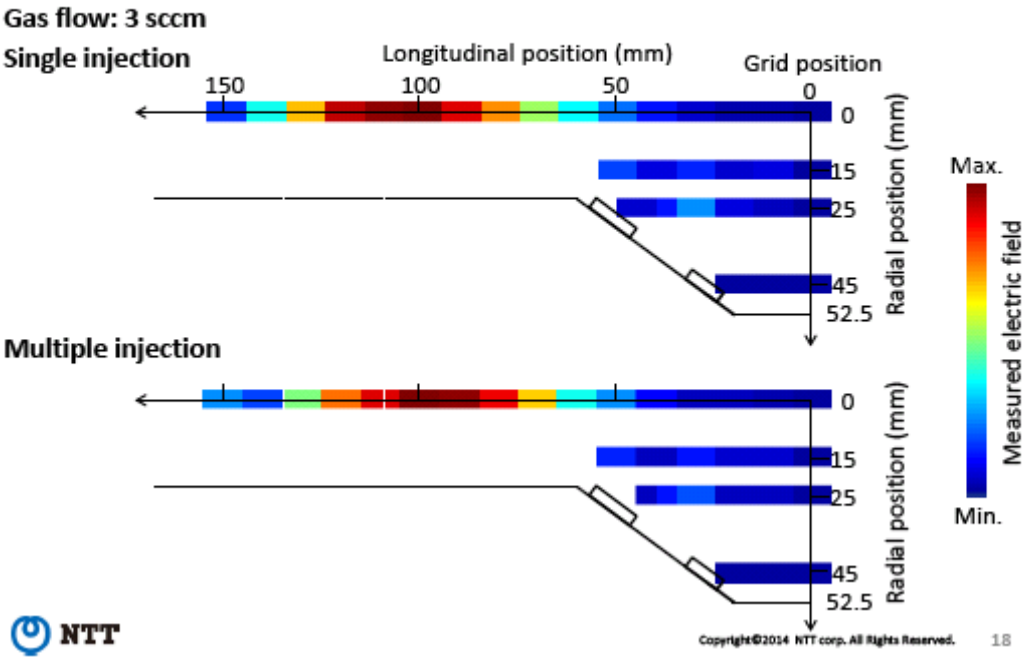
Measured Electric-field Distribution



Measured Electric-field Distribution

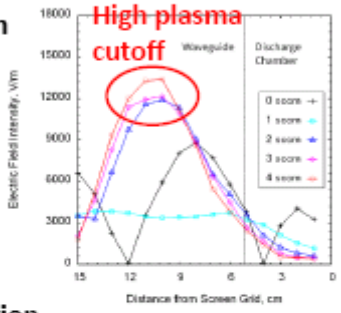


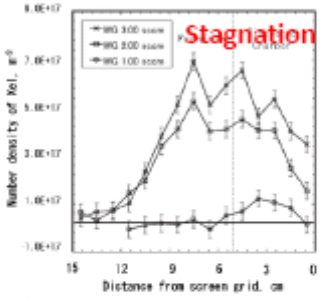
Results of Electric-field Measurements

Electric-field distribution

Xe I 828.16 nm density distribution

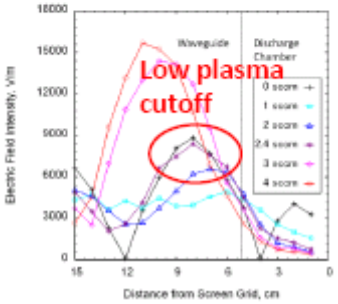
Single injection

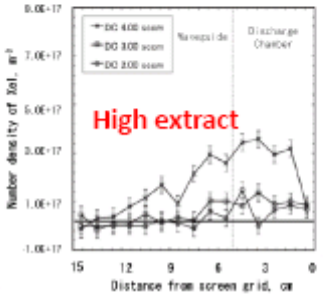




Multiple injection

Reduction of





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Conclusions

- Metal-free electric-field sensor is based on the pockels effect with only dielectric materials.
- Outstanding properties excepting sensitivity.
  - ✓ Frequency response: 20 kHz to 180 GHz
  - ✓ Minimum detectable electric field: < 60 mV/m/√Hz
  - ✓ Polarization discrimination ration: > 50 dB
- Applicabilities have been reported in some EMC applications.
  - ✓ Plasma measurements.
- In the future work, the sensitivity and stability will be improved with promising EO polymer and by establishing feedback systems.

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