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Design of omnidirectional Rydberg atomic sensors loaded with electric field enhancement structure using characteristic mode analysis

Key words: Rydberg atomic sensor; Characteristic mode; Electric field enhancement structure

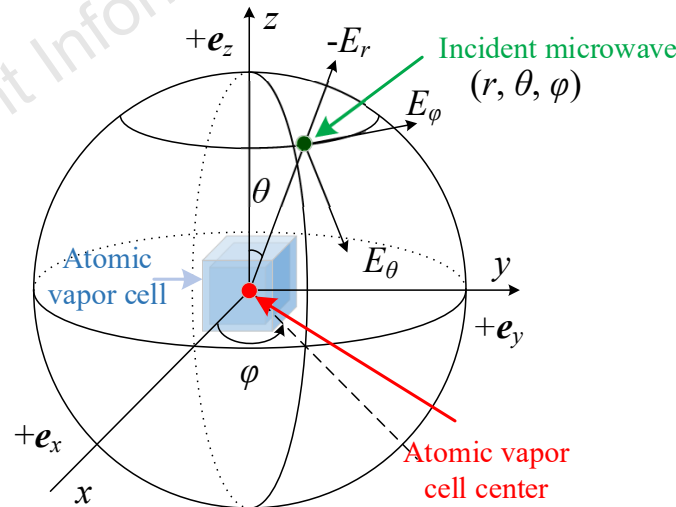
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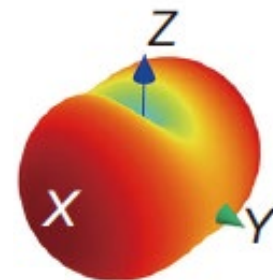
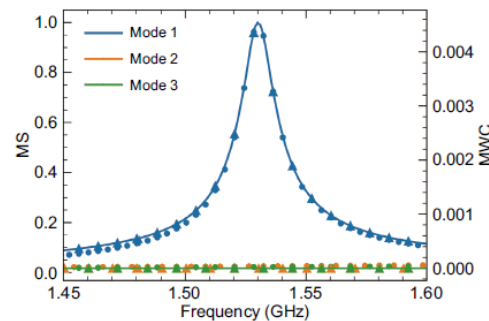
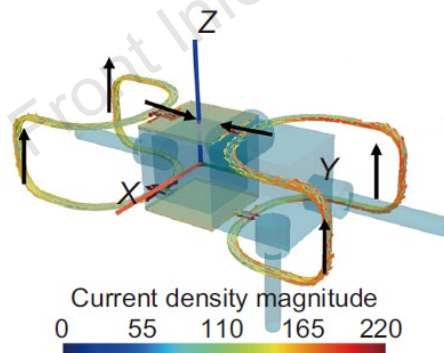
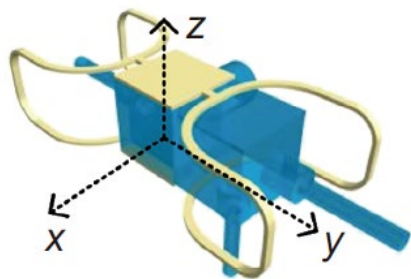
Motivation

- ❑ Rydberg atomic sensors (RASs) are used in quantum measurement systems for their high sensitivity to electric fields.
- ❑ Integration of electric field enhancement structures (EFESs) with RASs can further enhance detection sensitivity.
- ❑ However, analyzing the directional response of EFESs and the three-dimensional patterns of RASs is challenging due to the complexity of full-wave numerical simulations. Each angle needs to be calculated individually, similar to solving a radar cross-section (RCS) problem.



Main idea

- ❑ A method using characteristic mode (CM) analysis is proposed to study the omnidirectional performance of RASs loaded with EFESs.
- ❑ This method reduces the complexity of solving EFES patterns by calculating the reception pattern using modal currents and their coefficients, avoiding time-consuming full-wave simulations.



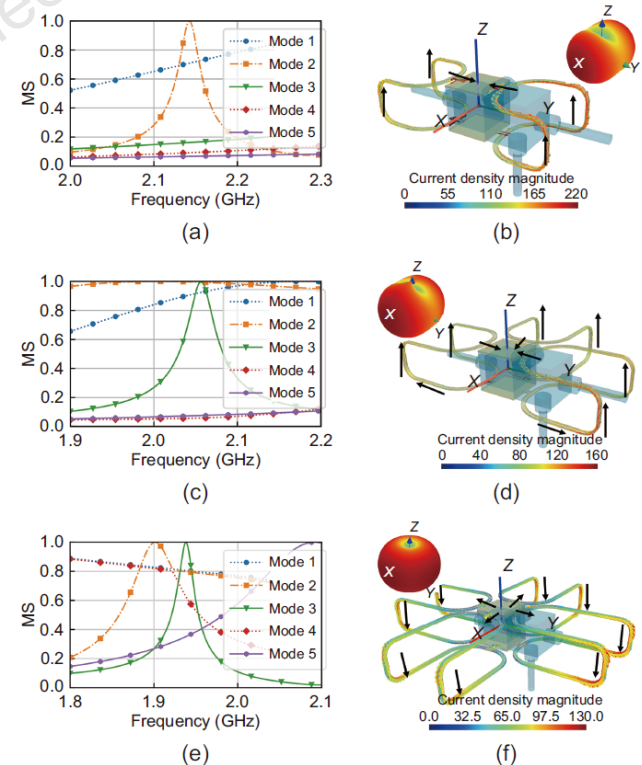
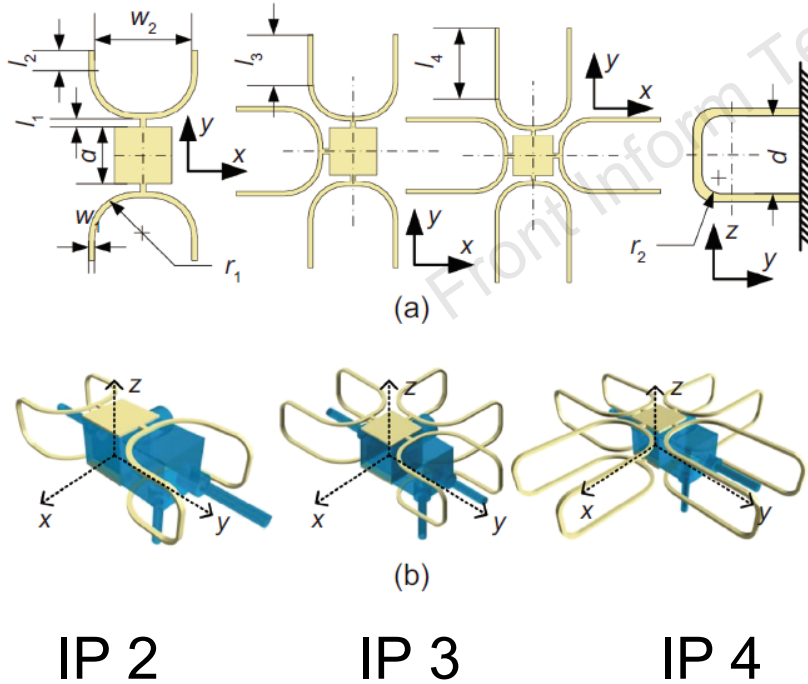
1) Characteristic mode (CM) analysis

- According to CM theory, the reception pattern can be calculated by a series of modal currents and their corresponding coefficients.
- The coefficients can be analytically determined, significantly reducing the complexity of solving EFES patterns.

$$\begin{aligned} \mathbf{J}(\mathbf{r}) &= \sum_n^n a_n \mathbf{J}_n(\mathbf{r}) & G_E(\alpha, \varphi, \theta) &= \frac{|\sum_n^n a_n \mathbf{E}_n(\mathbf{r}_0)|}{|\mathbf{E}_1(\mathbf{r}_0)|} \\ \mathbf{E}(\mathbf{r}) &= \sum_n^n a_n \mathbf{E}_n(\mathbf{r}) & &= \left| \frac{\sum_n^n \frac{\langle \mathbf{E}_{\text{inc}}(\alpha, \varphi, \theta), \mathbf{J}_n \rangle}{1 + j\lambda_n} \mathbf{E}_n(\mathbf{r}_0)}{\mathbf{E}_1(\mathbf{r}_0)} \right| \\ \mathbf{H}(\mathbf{r}) &= \sum_n^n a_n \mathbf{H}_n(\mathbf{r}) & &\approx \left| \sum_n^n \frac{\langle \mathbf{E}_{\text{inc}}(\alpha, \varphi, \theta), \mathbf{J}_n \rangle}{1 + j\lambda_n} \mathbf{E}_n(\mathbf{r}_0) \right| \end{aligned}$$

2) Experimental setup

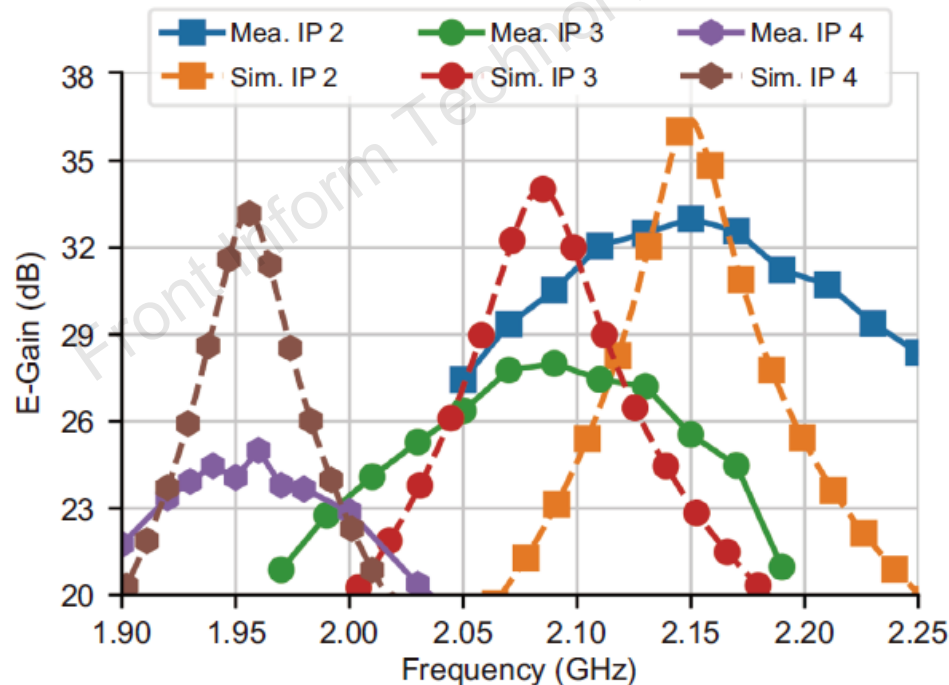
- ❑ Construct three prototypes with different current path configurations (IP 2, IP 3, IP 4).
- ❑ Use a uniform plane wave as the incident wave to study the directional response.
- ❑ Analyze the modal currents and calculate the electric field gain (E-Gain) patterns using CM analysis.



3) Major results

□ Prototype resonance and performance:

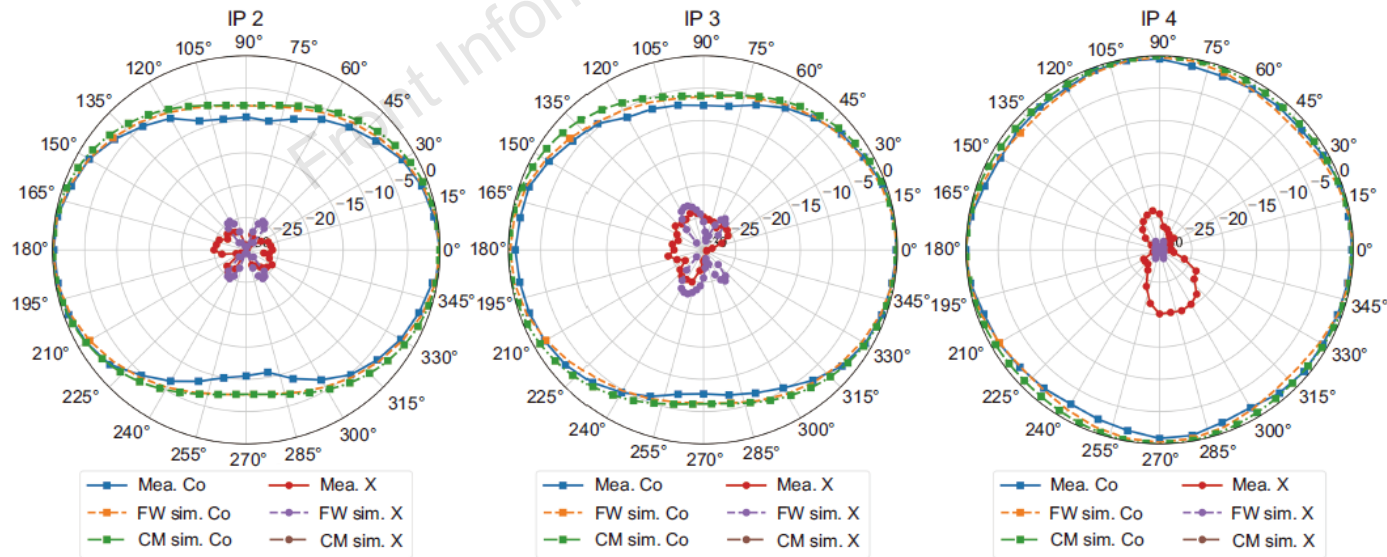
- The final model (IP 4) resonates at 1.96 GHz, achieving an electric field gain of 25 dB and an out-of-roundness of 2.4 dB.
- The omnidirectional performance is improved with the increase in the number of current paths.



3) Major results

□ Pattern analysis:

- The directionality of the IP series models decreases as the number of paths increases, indicating better omnidirectional performance.
- The measured E-Gain patterns show good agreement with the simulated patterns, demonstrating the effectiveness of the CM method in analyzing EFES patterns.
- The patterns calculated using CM analysis closely match the full-wave simulation results.



Conclusions

Summary:

- The proposed CM analysis method provides a feasible and efficient way to design omnidirectional EFESs for RASs.
- The method simplifies the pattern analysis process and reduces the computational complexity compared to traditional full-wave simulations.
- The fabricated prototypes demonstrate good omnidirectional performance and enhanced detection sensitivity, highlighting the potential of the proposed method for future applications in quantum measurement systems.

Future work:

- Further optimization of EFES designs to achieve higher E-Gain while maintaining omnidirectional performance.
- Exploration of the method's applicability to other types of atomic sensors and higher frequency ranges.



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Yi LIU received his B.S. and M.S. degrees in Electronic Science and Technology, and Ph.D. degree in Information and Communication Engineering Technology from NUDT in 2011, 2013, and 2018, respectively. He is currently an associate professor at the College of Electronic Science, NUDT. His current research interests include analysis and design of new types of antennas and atomic sensors.