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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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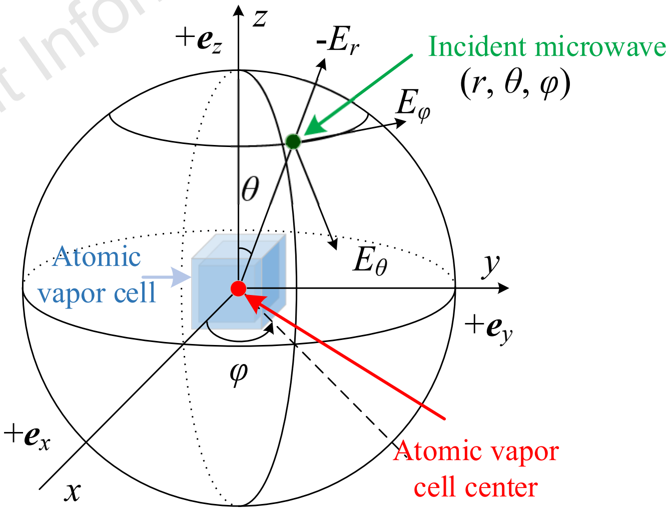
Motivation

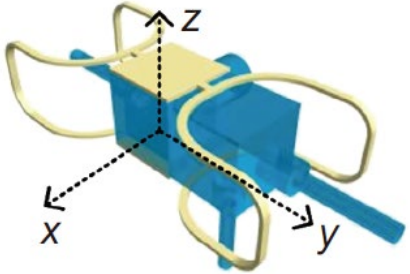
- Rydberg atomic sensors (RASs) are used in quantum measurement systems for their high sensitivity to electric fields.
- Integration of electric field enhancement structures (EFESs) with RASs can further enhance detection sensitivity.
- However, analyzing the directional response of EFESs and the three-dimensional 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.

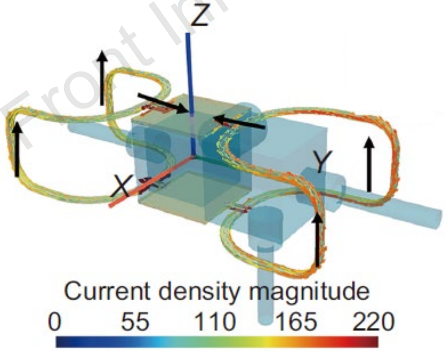


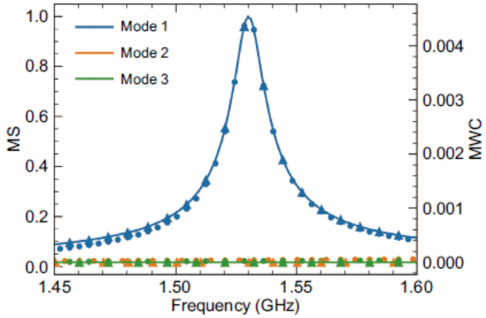
Main idea

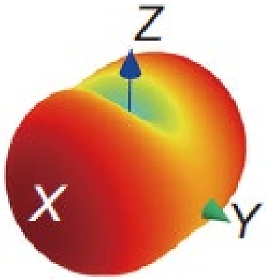
- A method using characteristic mode (CM) analysis is proposed to study the omnidirectional performance of RASs loaded with EFESs.
- This method reduces the complexity of solving EFES patterns by calculating the reception pattern using modal currents and their coefficients, avoiding time-consuming full-wave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


EFES → Modal E-field and modal current → MWC → Modal pattern









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.

$$\boldsymbol{J}(\boldsymbol{r}) = \sum^{n} a_n \boldsymbol{J}_n(\boldsymbol{r})$$

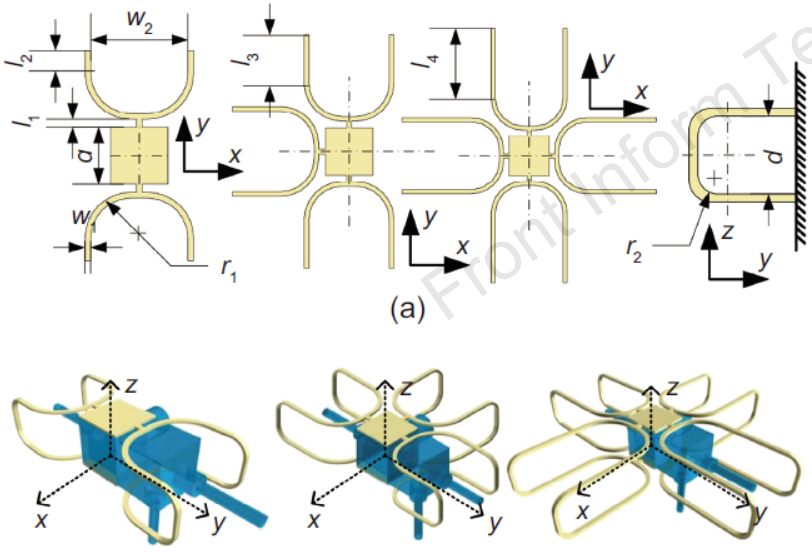
$$\boldsymbol{E}(\boldsymbol{r}) = \sum^{n} a_n \boldsymbol{E}_n(\boldsymbol{r})$$

$$\boldsymbol{H}(\boldsymbol{r}) = \sum^{n} a_n \boldsymbol{H}_n(\boldsymbol{r})$$

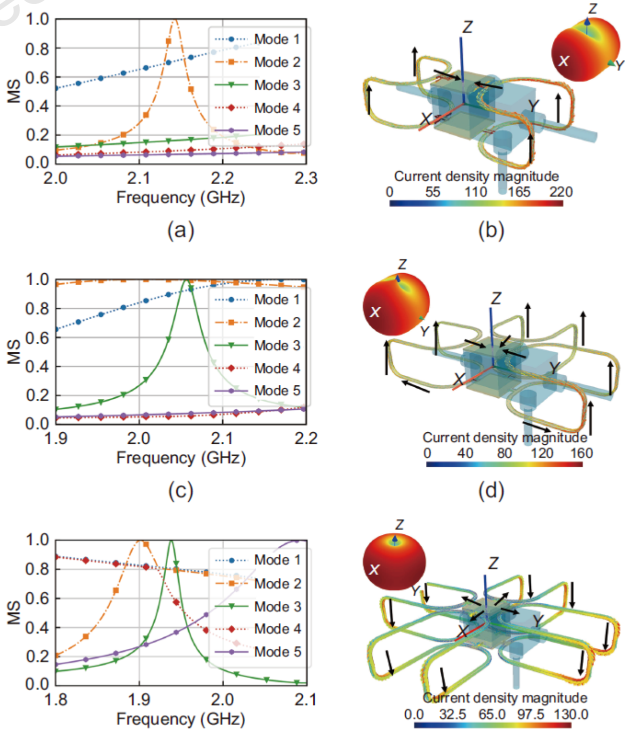
$$\begin{aligned} G_{\mathrm{E}}(\alpha, \varphi, \theta) &= \frac{|\sum^{n} a_n \boldsymbol{E}_n(\boldsymbol{r}_0)|}{|\boldsymbol{E}_1(\boldsymbol{r}_0)|} \\ &= \left| \frac{\sum^{n} \frac{<\boldsymbol{E}_{\mathrm{inc}}(\alpha,\varphi,\theta), \boldsymbol{J}_n>}{1+\mathrm{j}\lambda_n} \boldsymbol{E}_n(\boldsymbol{r}_0)}{\boldsymbol{E}_1(\boldsymbol{r}_0)} \right| \\ &\approx \left| \sum^{n} \frac{< \boldsymbol{E}_{\mathrm{inc}}(\alpha, \varphi, \theta), \boldsymbol{J}_n >}{1 + \mathrm{j}\lambda_n} \boldsymbol{E}_n(\boldsymbol{r}_0) \right| \end{aligned}$$

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.



IP 2 IP 3 IP 4



(a) (b)

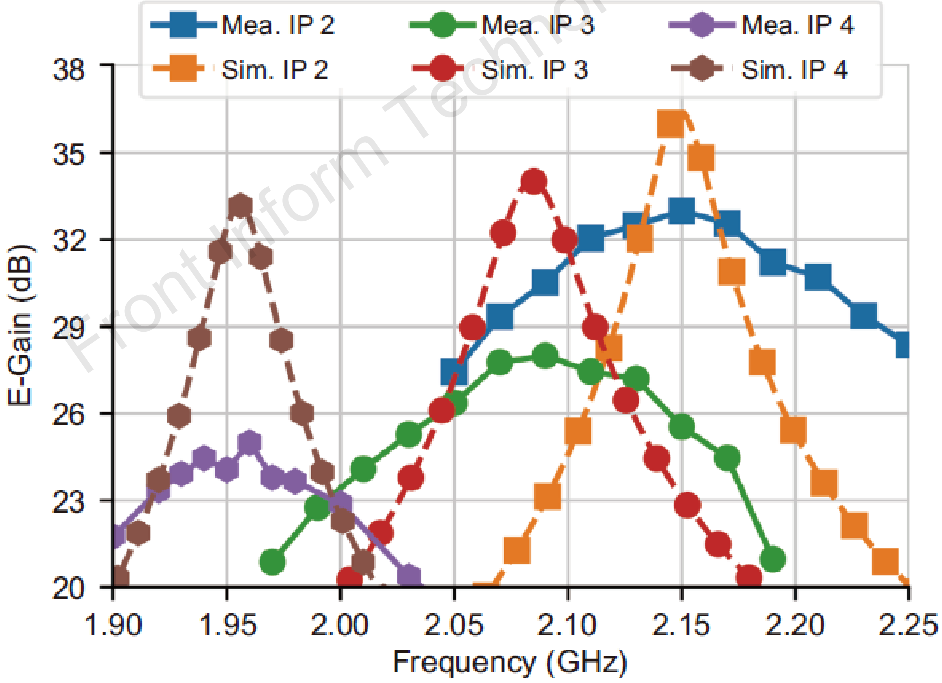
(c) (d)

(e) (f)

3) Major results

☐ Prototype resonance and performance:

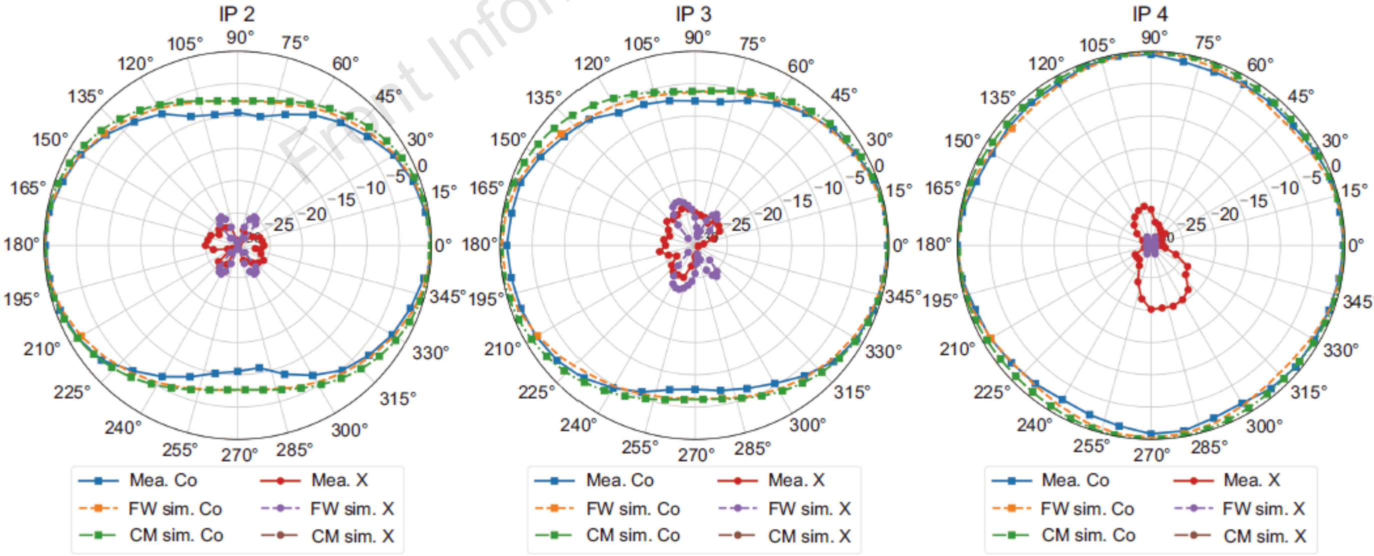
- The final model (IP 4) resonates at 1.96 GHz, achieving an electric field gain of 25 dB and an out-of-roundness of 2.4 dB.
- The omnidirectional performance is improved with the increase in the number of current paths.



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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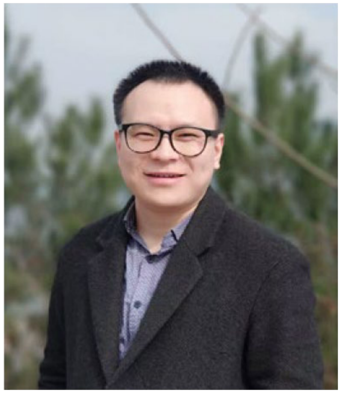

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