

On optical mode excitation in metal capillaries

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Abstract—The excitation of the E- and H- modes by focusing of a monochromatic light beam onto a hollow metal capillary (MC) entrance is theoretically detailed. As found, a numerical aperture sets a stringent bound on the number of excited optical modes, either when the beam is focused by a spherical lens onto the entrance of a circular MC or when a rectangular capillary is illuminated via a cylindrical lens. Transmission characteristics calculated in a general form provide grounding to use MCs as a means to enhance the Raman signals.

Index Terms—Hollow core metal waveguides, Raman signal enhancement

I. INTRODUCTION

Light trapping inside MC (or a glass capillary with metal lined inner walls) was found [1] to markedly - by decimal orders - enhance the Raman signals relative to those generated at conventional free-space excitation. The losses on walls, which limit the usable MC lengths, require a still missing multimode analysis appropriate to visible light. Here, this issue (A) alongside with the related problem of the mode spectrum (B) excited by focusing light onto a MC entrance is explored for both round and rectangular MCs.

II. METHODS AND RESULTS

The problem B is readily solved since the fields produced by spherical (S) or cylindrical (C) lenses are known functions dependent on $\rho\alpha = \alpha ka$, where α denotes the numerical aperture, $k = \omega/c$ and a is the MC radius or a side of the rectangle. To a good approximation, only E_{1m} - and H_{1m} - modes are excited in case S with the amplitudes proportional to the overlap integral $\mathcal{O}$:

$$\mathcal{O}(\rho\alpha, \chi) = \int_0^1 J_1(\rho\alpha t) J_0(t\chi_{1m}^{E/H}) dt \quad (1)$$

where $\chi_{1m}^{E/H}$ are the mode self values, $J_n(\chi)$ is the Bessel function and the condition $ka = \chi_{1m}^{E/H}$ defines the cutoff boundary between the propagating and evanescent modes. Actually, $\mathcal{O}$ suddenly drops when $\chi_{1m}^{E/H} \geq \rho\alpha$ (Fig. 1). Hence, only a small part of the propagating E/H modes is excited since, typically, $\alpha \ll 1$. At long enough path lengths L , as follows from the waveguide theory, only H_{1m} -waves survive. The calculated transmittance surfaces as functions of m and $L\xi/a$ (ξ is the surface impedance) allowed us to determine the effective propagation path lengths at different values of $\rho\alpha$. At large $\rho\alpha$, the integrated (over m) transmittance decreases with L almost monoexponentially, despite its partial contributions

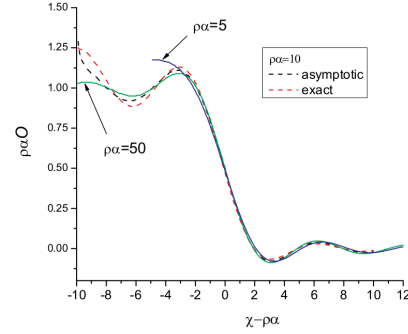


Fig. 1. Behavior of the overlap integral vs. the continuous variable χ near the cutoff boundary for different values of $\rho\alpha$.

decay with quite different rates. As found, the $\lambda = 0.5\mu m$ H_{1m} -waves can propagate about 15 m in a flawless round ($a=1mm$) silver MC thus furnishing [2] the Raman signal enhancement by three decimal orders. Although this assessment can be substantially worsened for real MCs, the gain is quite magnificent and, qualitatively, is in accord with experimental findings [1]. Similar results were obtained for a rectangular ($a \times b$) MC (case C) illuminated via a cylindrical lens whose axis $Ox \parallel b$. The excited E_{0n} - and H_{0n} -modes are then determined by the sine integral $Si(\rho\alpha - \pi n)$ and reveal a cutoff at $n = \alpha ka/\pi$ similar to that on Fig. 1.

III. CONCLUSIONS

As our calculations show, the use of round and rectangular MCs can enhance the Raman intensity by decimal orders. When light is focused on the MC entrance hole, the number of modes excited therewith can be easily controlled by aperture. The field-space metric modification allowed us to establish new mathematical relationships among the self characteristics.

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REFERENCES

- [1] S. Rupp, et al., "Improving the Detection Limit in a Capillary Raman System for In Situ Gas Analysis by Means of Fluorescence Reduction," *Sensors*, vol. 15, pp. 23110–23125, 2015.
- [2] V.V. Vitkin, et al., "Metal Capillaries: New Prospects for Application in Raman Spectroscopy," *ICLO-2024*; <https://ieeexplore.ieee.org/document/10624059>.