GENERAL THEORY OF IMAGE FORMATION TO ADDRESS RESOLUTION LIMIT OF ALL OPTICAL MICROSCOPY

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KEY WORDS: 3-D aperture, OTF, frequency cutoff, double-sided Feynman diagram

Depending on the type of optical microscopy in which diverse light-matter interactions are employed to form images, the resolution limits differ from one another. To compare the optical resolutions of all microscopy, the unified image-formation theory beyond the characterization of individual microscopy is required. First we generalized some concepts as follows: i) a target to be observed is *i*-th order linear/nonlinear susceptibility $\chi^{(i)}$, ii) diffraction is replaced by quasi phase matching, and iii) the vacuum field is involved as one of the excitation fields in incoherent interaction. Second we defined "3-D aperture" in spatial-frequency domain as the contribution rate of Fourier components in object to the image formation. Because the 3-D aperture can always be defined even when optical transfer functions (OTF) cannot be defined in some microscopy, the 3-D aperture is more fundamental and useful physical quantity to express the resolution limit than the OTF.

We develop an intuitive technique to calculate the 3-D aperture of all microscopy. Surprisingly, there exists the strong connection between the 3-D aperture and double-sided Feynman diagram depicting light-matter interaction. The diagram includes some arrows representing electric fields, in which each arrow corresponds to the 3-D pupil function, following the rules we derived. The 3-D aperture can be calculated from the convolution of all of the corresponding 3-D pupil functions in a diagram of interest. According to our theory, the type of interaction determines the upper limit of frequency cutoff of far-field microscopy if no *a priori* information about the sample exists. We also refer to optical coherence tomography using four-dimensional formulation (4-D aperture) to compare optical microscopy.

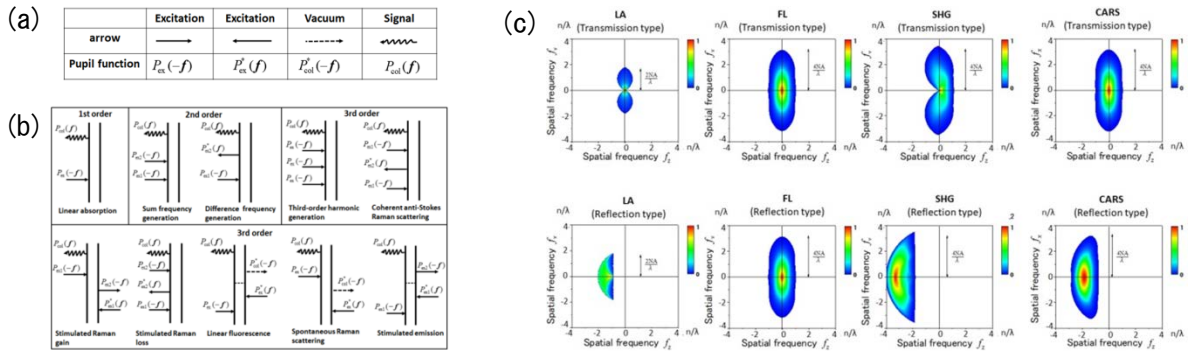

Fig. 1. (a) Correspondence rule between arrows and pupil functions in confocal microscopy. (b) Diagrams for some interactions. Solid, dotted, and wavy arrows denote excitation, vacuum, and signal field. (c) Examples of 3-D apertures. NA is 1.2 (water). λ is excitation wavelength. $P_{ex}(\boldsymbol{f})$ and $P_{col}(\boldsymbol{f})$ represent 3-D pupil functions of excitation and signal-collection systems, respectively. LA: linear absorption. FL: fluorescence.