Tunable spatial mode beating for distributed sensing.

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Abstract: We propose a novel interrogation method, which is suitable for distributed sensing of fluorescent yields. In contrast to temporal multiplexing schemes the spatial resolution is not limited by the fluorescence lifetime. We describe the practical implementation of the method in integrated optics.

Principle of distributed chemical sensing: An array of chemically sensitive spots is arranged on the surface of an integrated optical stripe waveguide. All spots contain the same fluorescent molecular group which acts as a 'chromophore', transducing by its fluorescent yield the concentration of a chemical species μ in an analyte. Each spot may be sensitized for the detection of a different species, $\mu = 1...M$. When optically pumped, the fluorescent intensity I_μ from the μ-th spot is in simple cases given by $I_\mu = Y_\mu P_\mu$. Here $Y_\mu = c_\mu S_\mu$ is the fluorescent yield of spot μ in response to the concentration c_μ of its particular species, S_μ is a normalized sensitivity, and P_μ is the pump power density at spot μ. By such an arrangement, chemical analysis is reduced to the optical problem of determining the fluorescent yields Y_μ of the M spots. Only this optical problem is addressed in the present investigation. Actually, we analyse the more fundamental problem of determining a general distribution $Y(z)$ of fluorescent yield from an observation of $I(z) = Y(z)P(z)$.

Measuring the distribution of fluorescent yield $Y(z)$. The stripe waveguide is designed to support two modes of the same polarization. Laser light of optical frequency ω is coupled into both modes simultaneously, launching optical powers P_1 and P_2 which propagate along z direction with propagation constants β_1 and β_2 and excite the fluorescence. The chromophore molecules in the superstrate 'see' the pump power distribution resulting from the superposition of the modal fields, $P_\omega(z) = q_1 P_1 + q_2 P_2 + q_{12}\sqrt{P_1 P_2}\cos[K_\omega z + \Phi_\omega]$ with $K_\omega = \beta_2(\omega) - \beta_1(\omega)$ and with certain coefficients q_1, q_2, q_{12}. The power $P_\omega(z)$ varies sinusoidally along z due to 'spatial beating' of the two modes. The spatial beat period $\Lambda_\omega = 2\pi/|K_\omega|$ depends on the frequency ω of the pump laser. Exploiting the dispersions $\beta_{1,2}(\omega)$ of the waveguide modes, Λ_ω can be varied in a controlled manner by tuning the laser, thus modifying the pump pattern $P(z)$. When fluorescent light from all points along the guide is collected by a single detector, a signal $U(\omega)$ results which permits, in principle,

determination of the unknown distribution $Y(z)$.

To explain the procedure of recovering $Y(z)$, we simplify the analysis by assuming q_1, q_2, P_1, P_2, and q_{12} to be independent of ω, moreover $\Phi_\omega = 0$. We decompose $U(\omega) = \int I(z)dz = \int Y(z)P(z)dz$ into a constant and a frequency-dependent part, $U(\omega) = U_{DC} + U_{AC}(\omega)$, where $U_{AC}(\omega) = q_{12}\sqrt{P_1 P_2}\int Y(z)\cos(K_\omega z)dz$. It is obvious that $U_{AC}(\omega)$ is the cosine Fourier transform of $Y(z)$. Therefore, $Y(z)$ could be recovered from $U_{AC}(\omega)$ by an inverse transform if $U_{AC}(\omega)$ were known for all ω. In practice $U_{AC}(\omega)$ can be measured only over a narrow range $\Delta\omega$ of laser frequencies (typically a few %) limited by the width of the excitation spectrum of the chromophores. We can solve this problem by a 'spatial demodulation' technique. All fluorescent spots are modulated spatially by a square-wave pattern of spatial frequency K_M, thus generating a lower spatial sideband at $K = K_\omega - K_M = 2\pi/\Lambda$. While the laser is tuned, the collected light is low-pass filtered and from the signal $U_{M,AC}(\omega)$ it is possible, then, to recover $Y(z)$. Apart from constant factors $Y(z) \propto \int U_{M,AC}(\omega)\cos([K_\omega - K_M]z)d\omega$. The attainable spatial resolution follows from the standard Fourier transform limit $\Delta z \cdot \Delta K_\omega \approx 2\pi$, where ΔK_ω is the variation of K_ω associated with $\Delta\omega$.

Experimental. For a practical implementation, a guide with large dispersion $dK_\omega/d\omega$ was used in the form of a single-core stripe waveguide, fabricated by field-assisted K^+-Na^+-exchange in soda-lime glass, Figure 1. Operating near $\lambda = 600$ nm it has a beat frequency of $K_\omega \approx 350$ cm^{-1}, corresponding to $\Lambda_\omega \approx 180$ μm. For a variation $\Delta\lambda = 30$ nm of the pump wavelength a dispersion of $\Delta K_\omega \approx 9$ cm^{-1} was achieved, permitting a spatial resolution of $\Delta z \approx 0.7$ cm. In a guide of length $L = 3$ cm a number $M \approx 5$ spots may be expected to be resolved. The contrast factor $q_{12}/\sqrt{q_1 q_2}$ of the excitation pattern is optimized by covering one half of the stripe waveguide with Teflon AF, and the other half with Nile Blue A Perchlorate doped PMMA. The spatial modulation K_M of the fluorescence was simulated by a grating mask having openings of $l \approx 50$ μm in close proximity to the guide. When the laser was tuned through $\Delta\lambda$ the variation of the beat pattern was clearly recorded, ranging from $\Lambda > 3$ cm to $\Lambda < 0.7$ cm, as expected. Experiments to demonstrate the resolution of separate fluorescent spots on the guide will be reported at the Conference.

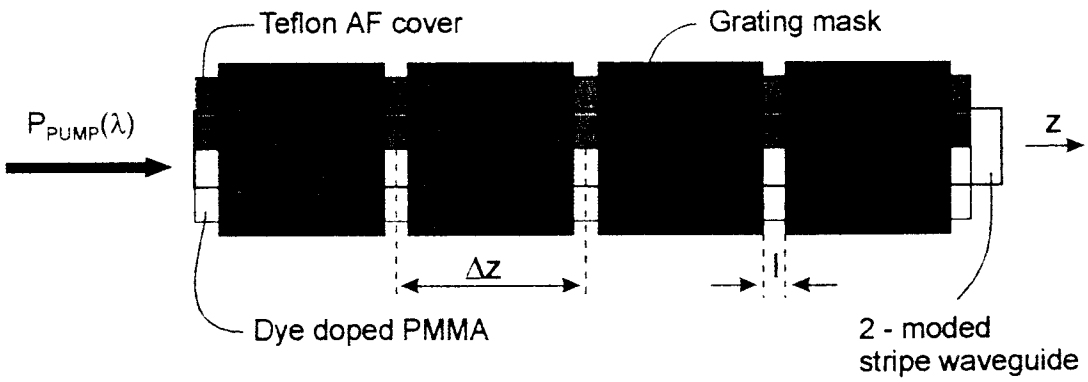

Figure 1 : Configuration of experimental device