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Optical Solitons and Eigenvalue Communications

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Optical solitons in optical fibers were discovered by Hasegawa and Tappert in 1973 [1] and have been actively studied more than 50 years for applications not only in long distance transmission technology but also fiber laser technology. Optical solitons are known to preserve the eigenvalues in the inverse scattering transform (IST)[2] thus the eigenvalues can be used as robust information carriers. If several eigenvalues and their combinations are used in a soliton as information carrier, the transmission data rate can be increased drastically. Based on the concept, Hasegawa and Nyu proposed eigenvalue communication in 1993[3].

In this talk, the impact of Hasegawa's pioneering work in optical solitons and eigenvalue communications on modern optical communication technologies are introduced and analyzed briefly.

The nonlinear Schrödinger equation (NLSE) which describes behavior of the complex envelope of electric field propagating in a nonlinear anomalous dispersion fiber is given by

$$i\frac{\partial q}{\partial Z}+\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+|q|^2 q=0\ , \qquad (1)$$

where Z, T, and $q(Z, T)$ are the normalized quantities of propagation distance, time moving with the group velocity, and complex envelope of electric field, respectively. Equation (1) can be solved analytically by using the IST [2]. The eigenvalue equation associated to Eq. (1) is given by

$$i\frac{\partial\psi_1}{\partial T}+q\psi_2=\zeta\psi_1\,,\qquad -i\frac{\partial\psi_2}{\partial T}-q^*\psi_1=\zeta\psi_2\,, \qquad (2)$$

where ζ is the complex eigenvalue and $\psi_\ell\,(Z,T)\;(\ell=1,2)$ are the eigen functions. In the framework of IST, so far as q is a solution of Eq. (1), the eigenvalues ζ of Eq. (2) are invariables, even though the temporal waveforms and frequency spectra dynamically change during propagation in fiber. Therefore the eigenvalue is more ideal information carrier than the pulse's amplitude, frequency, and/or phase which are modulated in conventional formats in optical fiber communications.

When the initial input pulse, $q(Z=0,T)$, has only one eigenvalue, $\zeta=(\kappa+i\eta)/2$, the fundamental soliton solution is given by

$$q(Z,T)=\eta\,\mathrm{sech}\{\eta(T+\kappa Z-T_0)\}$$
$$\times\exp\left\{-i\kappa T+\frac{i}{2}(\eta^2-\kappa^2)Z+i\theta_0\right\}, \qquad (3)$$

where T_0 and θ_0 are real constants. In soliton communication proposed in [1], soliton pulse expressed by Eq.(3) is used as information carrier because its pulse shape is invariant for any Z.

Figure 1 shows the annual change of the number of citations for Hasegawa and Tappert's original work on optical soliton in anomalous dispersion fiber [1]. After almost 10 years silence, the number of citations has drastically increased since the middle of 1980s. The reason of the drastic phase change is the introduction of optical amplification technologies.

In 1993, Hasegawa and Nyu have proposed eigenvalue communication based on the concept that the eigenvalues ζ of Eq. (2) are invariables even when the initial input pulse, $q(Z=0,T)$, has multiple eigenvalues[3].

Figure 2 shows the annual change of the number of citations for Hasegawa and Nyu's original work [3]. After almost 20 years silence, the number of citations has drastically increased since 2013. The reason of the drastic phase change is the introduction of digital coherent technologies.

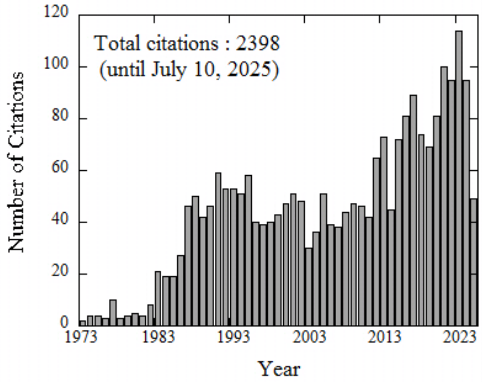

Figure1: Annual change of the number of citations for Hasegawa and Tappert's work [1] (from the Web of Science on July 10, 2025).

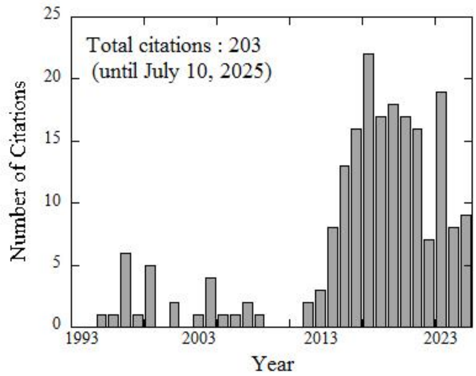

Figure 2: Annual change of the number of citations for Hasegawa and Nyu's work [3] (from the Web of Science on July 10, 2025).

References

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