# The Impact of Charles H. Townes on Nonlinear Optics

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*Invited Paper*

***Abstract*—This contribution reviews the impact of several of the pioneering contributions of Charles H. Townes on the development of the field of nonlinear optics. Research in the areas of stimulated Brillouin scattering, the Autler–Townes effect, and self-trapping of light are reviewed.**

***Index Terms*—Autler–Townes effect, nonlinear optics, self-action effects, self-trapping of light, stimulated Brillouin scattering.**

## I. Introduction

SHORTLY after the invention of the laser, a new field of scientific research known as nonlinear optics was created. This field developed as the result of the contributions of many individuals; the early history of the field is well documented in the monograph of Bloembergen [1]. One of the individuals who contributed to the establishment of the field of nonlinear optics was Charles H. Townes. In the present contribution we recall some of the early contributions of Prof. Townes to the field of nonlinear optics, and we trace how these contributions have made a lasting impact on this discipline.

## II. Stimulated Brillouin Scattering

The first reported demonstration of stimulated Brillouin scattering (SBS) was that of Chiao *et al.* [2]. Their experimental setup in shown in Fig. 1. The incident light beam used in this experiment was derived from a ruby laser (referred to as a maser in the figure in accordance with the customs of the time). Intense back-scattered radiation was observed to occur for sufficiently large input intensities. The Fabry–Perot interferometers were used to determine that back-scattered radiation was shifted downward in frequency by the characteristic acoustic (Brillouin) frequency of the medium, thus establishing that the light scattering did in fact occur as a consequence of SBS.

The nature of stimulated Brillouin scattering can be understood heuristically in terms of the diagram shown in Fig. 2. This figure shows a forward-going laser beam of amplitude $E_L$ scattering from a forward-going acoustic wave of amplitude $\rho$ to produce a backward-going (Stokes) field of amplitude $E_S$. SBS can be understood as occurring as a consequence of positive feedback: the beating of the laser field with the Stokes field tends to reinforce the intensity of the sound wave through the process of electrostriction, thereby increasing the intensity of the scattered Stokes wave. Quantitative arguments show that the SBS signal grows from thermal or quantum noise [3].

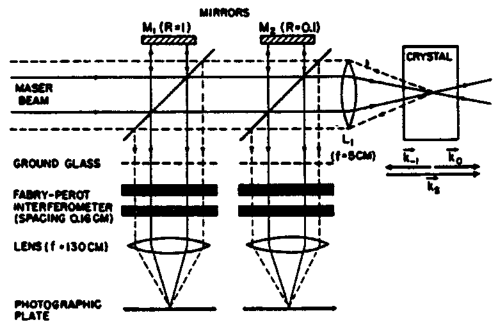


Fig. 1. Experimental setup of the first demonstration of stimulated Brillouin scattering.

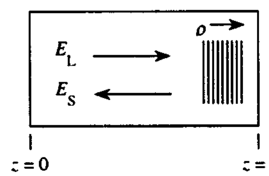


Fig. 2. Schematic description of stimulated Brillouin scattering.

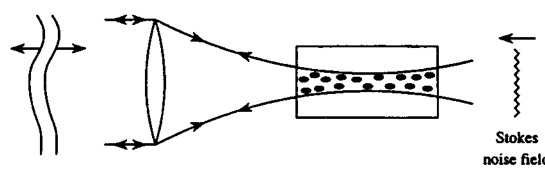


Fig. 3. Optical phase conjugation by stimulated Brillouin scattering.

SBS has been the subject of extensive investigation since the time of its discovery. The SBS process is known, for example, to lead to instabilities [4]–[6] and chaos [7] in the intensities of the scattered radiation. Perhaps the most striking implication of the process of SBS is its ability to produce a phase-conjugate wavefront, as first observed and explained by Zel'dovich *et al.* [8]. This process is illustrated in Fig. 3. Here a highly aberrated laser beam is focused into a Brillouin-active medium, and the SBS process creates a backward-travelling laser beam whose wavefronts everywhere replicate those of the incident beam. As explained by these authors, the origin of the phase conjugate nature of the scattered light can be traced to the highly nonuniform distribution of intensity in the focal region of the incident

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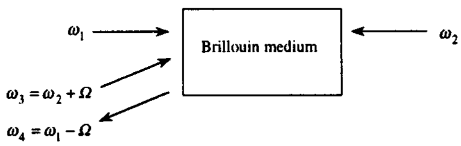


Fig. 4. Optical phase conjugation by Brillouin-enhanced four-wave mixing.

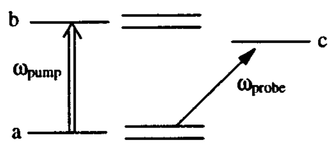

Fig. 5. Illustration of the Autler–Townes effect. The levels splitting is given by the Rabi frequency $\Omega = 2\mu E/\hbar$.

laser beam, which leads to a spatially nonuniform gain distribution that tends to favor the generation of a Stokes field with a phase-conjugate wavefront.

Phase conjugation can also be achieved through the related process of Brillouin-enhanced four-wave mixing (BEFWM). This process is illustrated in Fig. 4. BEFWM offers the possibility of generating the phase-conjugate of a signal wave ($\omega_3$) which is itself too weak to excite the normal SBS process. In the process of BEFWM, the signal beam ($\omega_3$) and the backward pump beam ($\omega_2$) differ by the Brillouin frequency $\Omega$ of the medium and thus interact to set up an intense sound wave in the material. The forward-going pump wave ($\omega_1$) scatters from this sound wave to generate the conjugate wave at frequency ($\omega_4 = \omega_3 - \Omega$). This process can produce a phase conjugate reflectivity much greater than unity and produce good efficiency for transferring the energy of the pump waves to the conjugate wave. For the special case in which the forward and backward pump waves differ by twice this Brillouin frequency of the medium ($\omega_2 = \omega_1 - 2\ \Omega$), the phase conjugate wave is at the same frequency as the signal waves ($\omega_3$) [9], [10]. BEFWM has important applications in the design of laser systems [11].

## III. Nonlinear Optical Analogs of the Autler–Townes Effect

In 1955, S. H. Autler and C. H. Townes published [12] an article in the Physical Review entitled "Stark Effect in Rapidly Varying Fields." This phenomenon is now known as the Autler–Townes effect. This effect is shown schematically in Fig. 5. A strong electromagnetic field drives the a–b transition of a material system. The rapid cycling of population between the lower and upper levels effectively splits these levels into doublets. This splitting can be monitored by measuring the absorption spectrum experienced by a probe wave connecting the ground level to some additional level, designated level $c$ in the figure. In the original paper of Autler and Townes the transitions were probed using rf and microwave fields, although more recent work has studied similar sorts of coupling when levels a, b, and c are separated by optical frequencies.

Fig. 6 shows how the optical properties of a two-level atomic system are modified by the presence of a strong laser field at frequency $\omega_c$. Part (c) of this figure shows how the absorption spectrum becomes modified under typical circumstances.

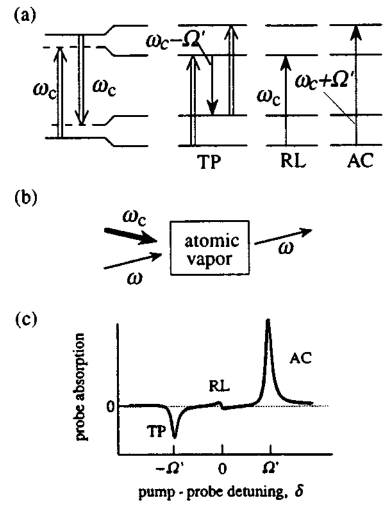


Fig. 6. (a) Modification of the optical properties of a two-level atomic system in the presence of an intense laser field of frequency $\omega_c$. $\Omega'$ is the detuned Rabi frequency, TP is the three-photon resonance, RL is the Rayleigh resonance, and AC is the ac-Stark shifted resonance. The modified energy level structure can be monitored by performing a pump-probe experiment of the sort shown in part (b), leading to a probe absorption spectrum of the form shown in (c).

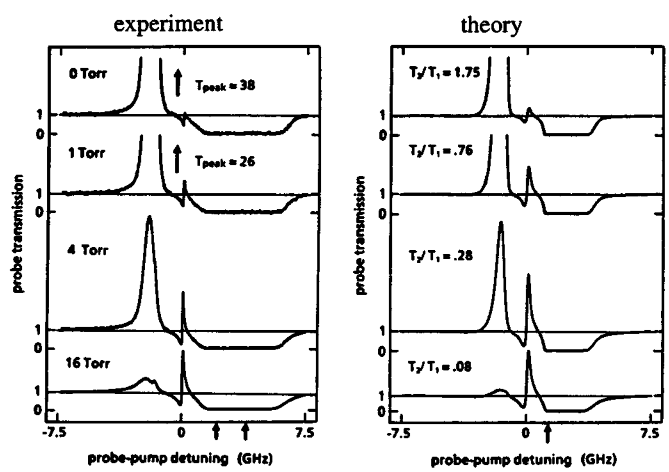


Fig. 7. Typical experimental and theoretical results showing the probe absorption spectrum as modified by an intense laser field. After Gruneisen *et al.*, [15].

This modified spectrum is often known as the Mollow spectrum [13]. Note that two of the spectral features can lead to the amplification of the probe field. Much research has been devoted to studies of how nonlinear optical properties are modified by strong, saturating laser fields [14]. One specific example is shown in Fig. 7 [15]. Here the measured probe absorption spectrum is shown for varying pressures of an argon buffer gas that was added the atomic sodium cell. One sees that the three-photon feature tends to be suppressed and the Rayleigh feature tends to be enhanced by increasing the buffer gas pressure. Also, as much as a 38-fold increase in probe intensity can occur as a consequence of the gain induced in the response.

Another recent development is the development of the process of electromagnetically induced transparency (EIT), a physical process that shares a similar origin with the Autler–Townes effect. EIT is a powerful technique that can be used to render a material system transparent to resonant laser

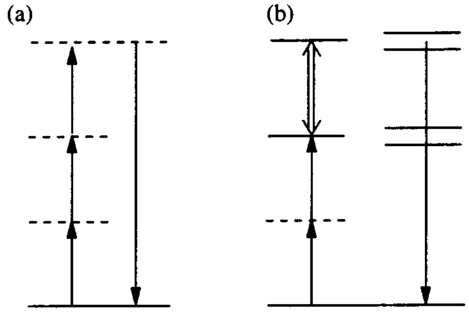


Fig. 8. Illustration of electromagnetically induced transparency (EIT). Part (a) shows normal sum-frequency generation without EIT with all optical fields detuned from resonance. Part (b) illustrates the EIT concept. The upper transition is resonantly excited by an intense laser field, leading to a splitting of the upper level which prevents the generated field from experiencing absorption. As a consequence of a subtle interference effect, the nonlinear response is not similarly eliminated.

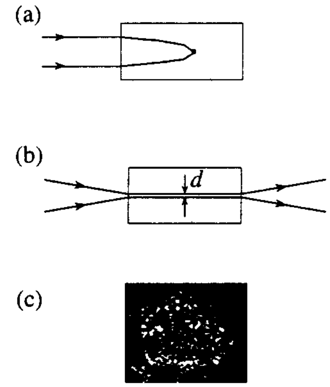


Fig. 9. Several self-action effects of light are illustrated: (a) self-focusing, (b) self trapping of light, and (c) the breakup of a beam of light into multiple filaments.

radiation, while retaining the large and desirable nonlinear optical properties associated with the resonant response of a material system [16]–[18]. The EIT process is illustrated in Fig. 8. EIT has been observed in several different experimental configurations [19]–[21], and its occurrence in still other configurations has been predicted theoretically [22]–[24]. Laboratory studies have confirmed that EIT can be used to enhance the efficiency of physical processes including nonlinear frequency conversion [21], [25], [26] and optical phase conjugation [27], [28]. In addition, it has been predicted that EIT can enhance the properties of a much broader range of processes including squeezed-light generation [29] and low-light-level photonic switching [30]–[32]. EIT has been observed both in atomic vapors [19]–[21], [25]–[28] and in solids [33], [34], and EIT plays a key role in the generation of slow light [35], [36] and its concomitant production of extremely large nonlinear optical effects [37]. Intimately related to EIT is coherent population trapping [38], which leads to processes such as high refractive indexes [39], [40].

## IV. Self-Trapping of Light

In 1964, Chiao *et al.* published a contribution titled "Self-Trapping of Optical Beams" in *Physical Review Letters* [41]. This paper showed how the nonlinear response of a material medium could modify the refractive index in such a manner that a beam of light could propagate long distances without spreading as a consequence of diffraction.

Today one often treats self-trapping as one of several related self-action effects of light. Some of these self-action effects are illustrated in Fig. 9. Self-focusing is a process in which a beam of light comes to a focus as a consequence of the nonlinear response of a material system. Self-trapping is the effect initially described by Chiao *et al.* in which the tendency of a beam of light to contract because of self-focusing exactly compensates the tendency of the beam to spread from diffraction. As shown by Chiao *et al.*, this balance can occur only if the power of the laser beam is exactly equal to the critical power given by $P_{cr} = \lambda^2/8n_0n_2$, where $\lambda$ is the vacuum wavelength of the light and the refractive index of the material can be represented as $n = n_0 + n_2 I$. Another self-action effect is laser beam filamentation, described initially by Bespalov and Talanov [42]. This process can occur only if the laser power $P$ is very much greater than $P_{cr}$. This process occurs as a consequence of the growth of aberrations on the laser wavefront through means of the process of forward four-wave mixing.

Recent research in all-optical logic for photonics applications has stressed the use of optical solitons. An optical soliton is a light field that propagates through a nonlinear medium without changing its pulse shape or beam profile [43]. Thus, a self-trapped beam of light is an example of an optical soliton. Many workers [44]–[46] have stressed the importance of optical solitons in technological applications. The concept of the optical soliton allows several different types of nonlinear propagation effects to be described in a related manner. Many of these effects can be described by an equation of the form

$$\frac{\partial A}{\partial z} + \frac{1}{v_g}\frac{\partial A}{\partial t} + \frac{1}{2} i\beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{1}{2ik}\nabla_T^2 = \frac{i n_0 n_2 \omega_0}{2\pi} |A|^2 A$$

where

| | |
|---|---|
| $v_g = (\partial k/\partial \omega)^{-1}$ | group velocity; |
| $\beta_2 = \partial^2 k/\partial \omega^2$ | measure of the dispersion in the group velocity; |
| $\nabla_T^2$ | transverse laplacian; |
| $\omega_0$ | central frequency of the pulse. |

The term involving $\beta_2$ describes the tendency of the pulse to spread in time due to dispersive effects, the term involving $\nabla_T^2$ describes diffraction, and the term involving $n_2$ describes self-phase modulation and self-focusing effects. The propagation of temporal solitons can be described by this equation by discarding the transverse laplacian, whereas the properties of self-trapped light beams (spatial solitons) can be described by this equation by discarding the time derivatives.

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His Ph.D. dissertation was supervised by Professor Charles H. Townes and involved the use of nonlinear optical techniques in infrared detection for astronomy. Professor Boyd joined the faculty of the Institute of Optics of the University of Rochester in 1977 and since 1987 has held the position of Professor of Optics. His research interest include fundamental studies of nonlinear and quantum optics, studies of the nonlinear optical properties of materials, and nonlinear optical interactions in atomic vapors. Professor Boyd has written two books, co-edited two anthologies, published over 180 research papers, and has been awarded four patents. He is past-chair of the Division of Laser Science of the American Physical society.