The third area is related to the studies of optical bistable effects. Although the original idea of an optical bistable device was reported in 1969 based on a saturable absorber in a F-P etalon,[77] researchers' attention really started to focus on this subject only after the first experimental demonstration of a real optical bistable device reported in 1975.[78] In this case, the mechanism of optical bistability was the optical field-induced refractive-index change of a nonlinear medium inside a F-P etalon,[79] which is called the nonlinear dispersion type of intrinsic optical bistable device. Another type of device, the so-called hybrid type of optical bistable device was demonstrated in 1977.[80] It was based on a second-order nonlinear electro-optical crystal placed inside a F-P etalon; the refractive-index change of the crystal was controlled by an external electric field that was proportional to the optical feedback from the F-P cavity. The significance of optical bistable studies is to explore possible ways to control light with light. The principles of optical bistability can be employed to accomplish a variety of vital functions such as optical switching, transistor, limiter, stabilizer, clipper, etc. In other words, optical bistable devices may be the key elements for optical fiber telecommunications, optical logical circuits, and optical computers in the future.

In the 1980's, nonlinear optics had been well established already. Although no many new effects or novel phenomena were reported, the momentum of nonlinear optics continuously increased in this decade. The research efforts focused on those areas such as nonlinear spectroscopic techniques with ultra-high spectral resolution or high temporal resolution, nonlinear optical applications for generation and control of ultra-short laser pulses, the optical phase-conjugation based on the degenerate four-wave mixing and backward stimulated scattering, optical bistability studies, photorefractive-effect studies, special techniques of second harmonic generation, and optical soliton studies.

1.3 FEATURES OF INTERACTION OF INTENSE LIGHT WITH MATTER

Regarding the interaction of light radiation with matter, the total number of newly discovered effects and phenomena after the advent of lasers is even larger than that of the optical effects and phenomena known before the invention of lasers. One may ask why so many new things can be found in a so short time period (only three to four decades). To answer this question, we should consider the essential differences between the light beams from laser devices and that from ordinary light sources. Only based on these differences, we can realize how powerful the laser radiation could be when it interacts with matter.

It is well known that the laser radiation is generated based on stimulated emission from a population inversion system, whereas the ordinary light is based on spontaneous emission from conventional light sources. Consequently, these two emission mechanisms lead to a great difference in the parameters used to describe the properties of light radiation.

The following are the common parameters to characterize a quasi-directional and quasi-monochromatic light field.

(1) ***Intensity*** is defined as

$$I = \frac{P}{S}, \tag{1.3-1}$$

where P is the total light power (in units of watt) and S is the cross section of the light beam (in units of m^2 or cm^2). The unit of the intensity is W/m^2 or W/cm^2.

(2) ***Spectral intensity*** is defined as

$$I(\nu) = \frac{P}{S\Delta\nu}, \tag{1.3-2}$$

where $\Delta\nu$ is the spectral width of the light radiation (in units of hertz). The unit of the spectral intensity is $W/(cm^2\ Hz)$.

(3) ***Brightness*** is defined as

$$B = \frac{P}{S\Omega} = \frac{I}{\Omega}, \tag{1.3-3}$$

where Ω is the divergent solid angle of the light beam (in units of steradian). The unit of the brightness is $W/(cm^2\ sr)$.

(4) ***Spectral brightness*** is defined as

$$B(\nu) = \frac{P}{S\Omega\Delta\nu} = \frac{I(\nu)}{\Omega}. \tag{1.3-4}$$

The unit of the spectral brightness is $W/(cm^2\ sr\ Hz)$.

(5) ***Photon degeneracy*** is defined as the average photon number contained in a single mode of optical field. This parameter is the basic quantity to describe the photon field in quantum electrodynamics and can be determined in the following way. For a quasi-directional and quasi-monochromatic light radiation the total photon number passing through a give beam section of S within a given time interval of Δt is

$$F = \frac{P\Delta t}{h\nu}, \tag{1.3-5}$$

where $h\nu$ is the energy of a single photon, h is Planck constant, ν is the frequency of light. On the other hand, the mode number (or phase-cell number) associated with the above F photons is given by

$$N = \frac{\Delta t}{\delta t} \cdot \frac{S}{\delta S} = \frac{\Delta t}{(1/\Delta\nu)} \cdot \frac{S}{(\lambda^2/\Omega)}. \tag{1.3-6}$$

Here $\delta t = 1/\Delta\nu$ is the longitudinal coherent time of the optical radiation, $\Delta\nu$ is the spectral width, $\delta S = \lambda^2/\Omega$ is the coherent section of the light beam, Ω is the solid angle of beam divergence. Assuming the light beam is non-polarized, there should be two independent polarization states; thus the photon degeneracy $\bar{n}$ can be finally determined by

$$\bar{n}(\nu) = \frac{F}{2N} = \frac{P}{(2h\nu/\lambda^2)S\Omega\Delta\nu}. \tag{1.3-7}$$

The photon degeneracy is a dimensionless quantity. From Eqs. (1.3-1) to (1.3-4) one can see that the light intensity represents the power density, the spectral intensity represents the power density within a unit spectral interval, the brightness represents the power density within a unit solid angle, and the spectral brightness represents the power density within a unit solid angle and a unit spectral interval, respectively. In addition, comparing Eq. (1.3-4) with Eq. (1.3-7) one can see that there is only a difference of factor $(2h\nu/\lambda^2)^{-1}$ between the spectral brightness $B(\nu)$ and the photon degeneracy $\bar{n}(\nu)$; therefore, they can be viewed as two equivalent quantities. According to conventional optics, the brightness of a light beam cannot be increased by passing it through any kinds of optical imaging or transmission systems. It can also be expressed in terms of quantum statistics that the total number of modes for a given photon ensemble cannot be compressed by any ordinary optical systems; therefore, the photon degeneracy cannot be increased by any types of ordinary optical devices. However, these two equivalent conclusions are no longer valid for lasers and nonlinear optical devices. It is well known that the brightness or photon degeneracy of a weak optical signal can be dramatically increased based on the coherent amplification through a lasing medium, a stimulated scattering medium, or an optical parametric amplifier system. For a laser oscillator system, the number of the total lasing modes can be greatly restricted by choosing appropriate cavity configurations and mode selection techniques. As a result, the photon degeneracy of the output laser beam can be extremely high.

According to the electromagnetic theory of light, on the other hand, the spectral intensity of a quasi-parallel laser beam is equal to the magnitude of the Poynting's vector of a monochromatic plane electromagnetic wave, i.e.,

$$I(\nu) = \frac{1}{2}\varepsilon_0 c n_0 |E(\nu)|^2, \tag{1.3-8}$$

where c is the speed of light in the free space, n_0 is the linear refractive index of the medium, and $E(\nu)$ is the electric field strength of the monochromatic plane wave. From Eqs. (1.3-2) and (1.3-8) one can see that the values of $I(\nu)$ and $E(\nu)$ can be significantly increased when the beam size of the light radiation is compressed by using a reverse beam-expander or a focusing optical system, which are often employed in the experimental studies of nonlinear optics.

In Table 1-1, we list the typical parameters of light radiation from the strongest ordinary light source (the sun) and from laser devices. From this table one can see that the spectral brightness as well as the photon degeneracy of the radiation from high peak-power laser devices can be 10^{15} to 10^{19}-times greater than that of the radiation from an ordinary light source (like the sun).

Table 1-1
Characteristics of radiation from ordinary light source and lasers

Parameters	Sun	Gas Lasers	Solid Lasers	*Q*-Switched or Mode-Locked Lasers
Monochromaticity ($\Delta\nu/\nu$)	white light	10^{-8}~10^{-13}	10^{-3}~10^{-8}	10^{-2}~10^{-6}
Directionality Ω (sr)	$6.8 \cdot 10^{-5}$ (on the earth)	10^{-5}~10^{-7}	10^{-6}~10^{-8}	10^{-6}~10^{-8}
Brightness (W/cm^2sr)	~10^3	10^4~10^8	10^7~10^{11}	10^{12}~10^{17}
Spectral Brightness (W/cm^2srHz)	~10^{-12}	10^{-2}~10^2	10~10^3	10^4~10^7
Photon Degeneracy	$\leq 10^{-2}$	10^8~10^{12}	10^{11}~10^{13}	10^{14}~10^{17}

In addition, the values of $I(\nu)$ and $E(\nu)$ of a laser beam can be further increased by using an optical focusing system as described above. In the sense of radiation potentials in interacting with matter and creating various nonlinear responses, the differences between ordinary light and laser light are mostly similar to the differences between conventional weapons and strategic nuclear weapons. Therefore, we can say that the light from ordinary light sources is a weak optical radiation characterized by $\bar{n} \ll 1$ and can only create an extremely low electric field strength. Based on this reason, all the nonlinear terms in the expression of the polarization (see Eq. (1.1-7)) can be neglected. By contrast, the laser radiation is an intense coherent light characterized by $\bar{n} \gg 1$ and can provide a much stronger optical-frequency electric field, which can even be comparable with the internal electric field of the atom or molecule. In such a case, the nonlinear terms of the polarization expression cannot be entirely neglected and may play a vital role for various nonlinear optical effects. Based on quantum statistics, a light radiation with $\bar{n} \ll 1$ manifests the feature of a shot noise field when it interacts with matter; whereas a radiation with $\bar{n} \gg 1$ manifests the feature of a coherent wave field when it interacts with matter. That is an alternative insight to understand why so many nonlinear optical effects (especially the coherent wave mixing effects in nonlinear media) can be observed only by using laser radiation but not ordinary optical radiation.

In summary, on the one hand, the parameters of laser radiation (such as power, beam divergence, pulse duration, wavelength, spectral width, polarization status, etc.) can be well controlled or modified based on existing laser techniques. On the one hand, there is a great variety of nonlinear optical media, which can be various materials (inorganic, organic, biological, etc.), in different physical states (solid, liquid, gas, plasma, liquid crystal, etc.), and with different reaction centers (molecules, atoms, ions, atomic nuclei, electrons, color centers, phonons, excitons, plasmons, etc.). So that, it is not surprising that so many new effects and novel phenomena in nonlinear optics have been found within only three to four decades since the 1960's.[81-112] These effects and phenomena are related to the intense light-induced opto-optical, opto-electric, opto-magnetic, opto-acoustic, opto-thermal, opto-mechanical, opto-chemical, and opto-biological interactions in optical media. Generally speaking, all these kinds of interactions can be used to develop various new techniques that may provide many advantages, such as high efficiency, high resonant selectivity, high spectral resolution, high temporal resolution, high spatial resolution, and high sensitivity.

1.4 THEORETICAL FRAMEWORK OF NONLINEAR OPTICS

Basically, two major theoretical approaches can be employed in nonlinear optics as well as in laser physics.[81-112] The first is the semi-classical theory, and the second is the quantum electrodynamical theory. The most essential feature of the semi-classical theory is that the media composed of atoms or molecules are described by the theory of quantum mechanics, while the light radiation is described by the classical Maxwell's theory. The key issue of semi-classical theory in nonlinear optics is to give the expressions of macroscopic nonlinear electric polarization for optical media. For this purpose, the density matrix method, which is a special approach based on both quantum mechanics and statistical physics, is used to derive the expressions for various orders of electric susceptibilities as $\chi^{(1)}$, $\chi^{(2)}$, $\chi^{(3)}$..., and the expressions for various orders of polarization components as