Chapter 2: Switching with Optics

Switches are one of the most important devices employed for manipulating optical signals, and are used in optical communication networks, optical displays, and light modulations.

Advantages of using optical switches:

1- Ultrafast switching speed of more than 50 GHz.
2- Massive parallelism.

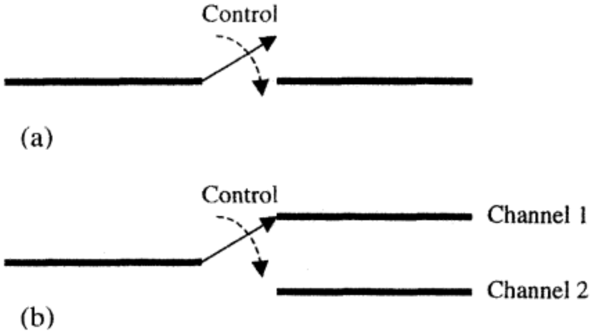
Kinds of optical switches:

1- Ultrafast all-optical switches using nonlinear optics.
2- Fast electro-optic modulators to convert electric data to optical ones.
3- Massive parallel switches using microelectromechanical systems (MEMS).

Optical switches can be classified into two configurations, as shown in Figure.

One is an ***on-off switch*** in which the input is connected to one output port. The other is a ***routing switch*** in which the input is connected to two or more output ports.

On-off switches are mainly used in modulation, light valves, and displays, while routing switches are used in connecting many nodes in networks.



Two configurations of optical switches, (a) On-off switch, (b) Routing switch.

There are several ways to control an optical switch, and the performance of the switch largely depends on the control mechanism. Traditional control mechanisms include:

1- Electro-optical effect
2- Acousto-optic effect
3- Magneto-optic effect
4- Thermo-optic effect
5- Piezoelectric effect
6- Electro-mechanical actuation

FIGURES OF MERITS FOR AN OPTICAL SWITCH

There are several basic parameters used for evaluating the performance of an optical switch. These include on-off ratio, bandwidth or switching time, insertion loss, power consumption, and cross talk between channels.

- The on-off ratio (also called contrast ratio) is the ratio of the maximum transmitted light intensity I_{max} to the minimum transmitted light intensity I_{min}, and is often described in decibels:

$$R_{\text{on}-\text{off}} = 10\log(I_{\max}/I_{\min}).$$

This ratio measures the quality of generated data by the switch and is related to the eventual error rate of the transmission system. An ideal switch would have an infinite on-off ratio ($I_{min} = 0$).

- Switching time (τ) measures how fast the switch can perform, and is defined as the time required for switching the output intensity from 10% to 90% of I_{max}.

It is related to the - 3 dB bandwidth ($\Delta\nu$)

$$\Delta\nu = 0.35/\tau \text{ Hz}.$$

- Insertion loss (L) describes the fraction of power lost when the switch is placed in the system. The insertion loss does not include the additional loss during switching, and is defined as

$$L(\mathrm{dB}) = 10 \log P_{\mathrm{out}}/P_{\mathrm{in}}.$$

where P_{out} is the transmission power when the switch is not in the system, and P_{in} is the transmitted power when the switch is in the system and adjusted to provide the maximum transmission.

- Power consumption is defined as the power consumed by the switch during operation. The consumed power will eventually turn into heat, and limit the number of switches or other devices can be put on a system unit. It will also set a demand on the power supply.

While the above parameters measure the performance of both on-off and routing switches, the final parameter, cross talk, only applies to the routing switches. It describes how effective a signal is isolated between two unconnected channels. Consider that a routing switch has one input and two outputs.

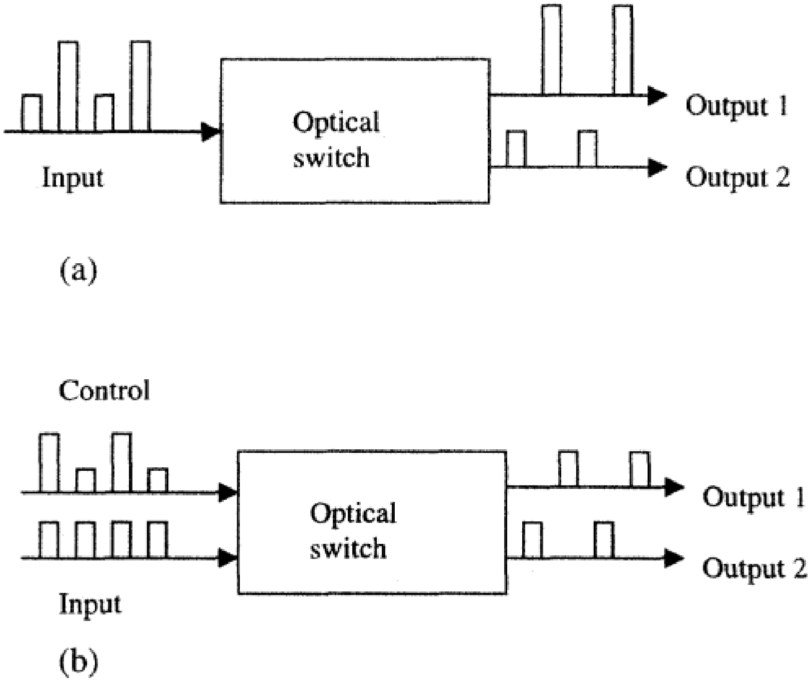
- When the input is connected to output channel 1 of the output, cross talk in this case describes how much of the input signal appears on channel 2. It is defined as

$$\text{Cross talk (dB)} = 10 \log(I_2/I_1),$$

where I_1 is the output intensity in the connected channel, and I_2 is the intensity in the unselected channel. Ideally, I_2 , should be zero.

ALL-OPTICAL SWITCHES

All-optical switches are nonlinear optical devices the output characteristics of which are controlled by the intensity of the input signal or by a separate optical signal for self-switching and controlled switching, respectively as shown in the figure:



All-optical switches, (a) Self-switching, (b) Controlled switching.

OPTICAL NONLINEARITY

Nonlinear optical effects have been used to switch and route optical signals or perform logic operations on them in a number of ways.

The key element in all-optical switches is a medium with significant nonlinear optical effect. The main materials property is an intensity dependent refractive index *n(I)*, where *I* is the total intensity of the optical field in the medium.

The nonlinear optical effect used in all-optical switching is the third-order effect, or the Kerr effect, where

$$n = n_0 + n_2 I.$$

Here n_0 is the linear refractive index and n_2 is the nonlinear refractive coefficient.

For many optical materials, n_2 is very small.

For example, silica glass has $n_2 = 3 \times 10^{-20}$ m^2/W.

Therefore, we cannot directly observe any change in refractive index at low light intensity.

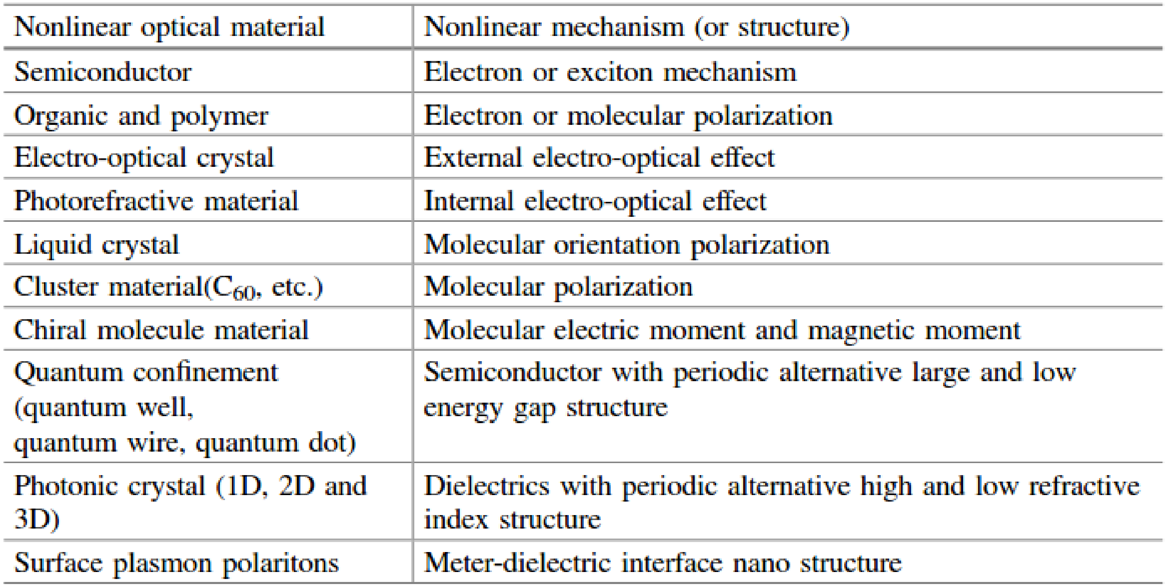
Nonlinear optical effect can be observed much more easily when we study the phase shift induced by the nonlinear refractive index. The phase shift of a medium is given by

$$\Delta\phi = \frac{2\pi}{\lambda} nl = \frac{2\pi}{\lambda} n_0 L + \frac{2\pi}{\lambda} n_2 I L,$$

where λ is the wavelength and L is the length of the medium over which the phase shift is accumulated.

The phase shift due to nonlinear effect can be significant when L is large, even though n_2 is small. Therefore, it is a logical choice that all-optical switches are based on nonlinear phase shift.

Table: Nonlinear optical materials and nonlinear mechanisms (or structures)



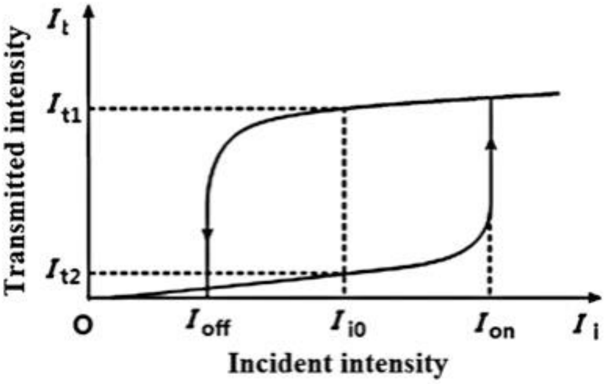
Nonlinear optical material	Nonlinear mechanism (or structure)
Semiconductor	Electron or exciton mechanism
Organic and polymer	Electron or molecular polarization
Electro-optical crystal	External electro-optical effect
Photorefractive material	Internal electro-optical effect
Liquid crystal	Molecular orientation polarization
Cluster material(C_{60}, etc.)	Molecular polarization
Chiral molecule material	Molecular electric moment and magnetic moment
Quantum confinement (quantum well, quantum wire, quantum dot)	Semiconductor with periodic alternative large and low energy gap structure
Photonic crystal (1D, 2D and 3D)	Dielectrics with periodic alternative high and low refractive index structure
Surface plasmon polaritons	Meter-dielectric interface nano structure

Optical Bistability

Definition of Optical Bistability

If an optical system under a given incident light intensity (I_{io}) exists two possible transmitted light intensities (I_{t1} and I_{t2}), and a recoverable and fast switching conversion between these two intensity states can be realized, then we say that this system possesses optical bistability (OB), as shown in Figure (a).

(a) Schematic diagram of the definition of optical bistability



(b) Characteristic curve of optical bistability

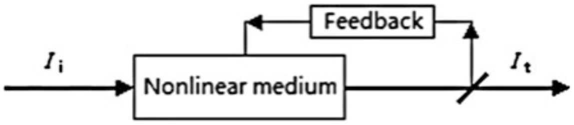
Figure (b) shows the characteristic curve for describing the relation of input intensity and output intensity (I_t - I_i curve) of the optical bistability system. It is clear that the transmitted light intensity is a two-value (or multiple-value) function of the incident light intensity.

Composition of Optical Bistable Devices

The optical device with optical bistability is called Optical Bistable Device (OBD).

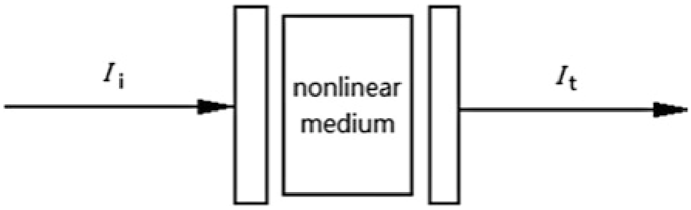
OBD is a kind of nonlinear optical devices, which are based on both factors (fig. (c)):

1- The nonlinear medium
2- The feedback mechanism.



(c) Composition principle of optical bistable device

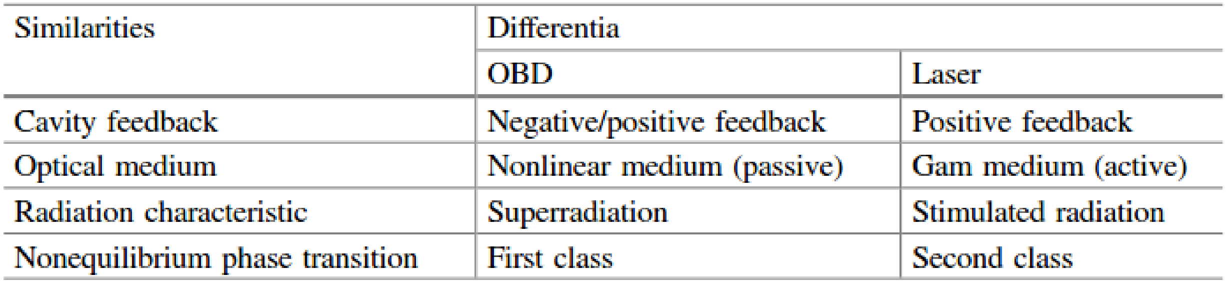
The typical OBD is an Fabry–Perot etalon filled with the nonlinear medium, as shown in Fig. (d). The feedback is completed by two reflective mirrors of F–P cavity.



(d) Optical bistable device consisted of a nonlinear F–P etalon

The F–P type optical bistable device looks like a laser. As we known that the laser is consisted of three elements: the gain medium, the optical resonant cavity, and the pump energy source. The composition of OBD also has three elements: the nonlinear medium, the feedback system and the input energy. A comparison between the optical bistable device and the laser is shown in Table.

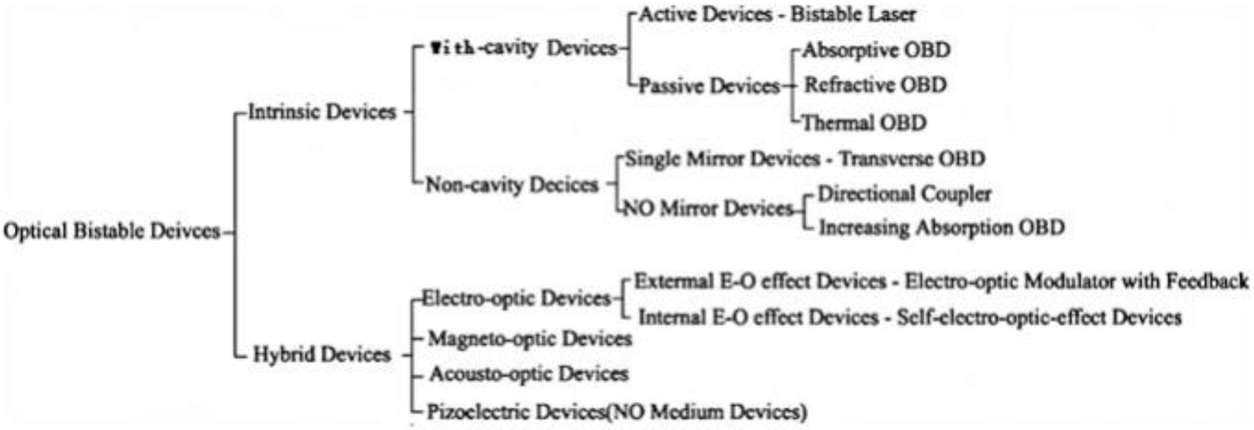
Table: Comparison between OBD and laser



Similarities	Differentia	
	OBD	Laser
Cavity feedback	Negative/positive feedback	Positive feedback
Optical medium	Nonlinear medium (passive)	Gam medium (active)
Radiation characteristic	Superradiation	Stimulated radiation
Nonequilibrium phase transition	First class	Second class

Classification of Optical Bistable Device

Classified by feedback methods, the OBD is mainly divided into two kinds: the intrinsic optical bistable device and the hybrid optical bistable device.

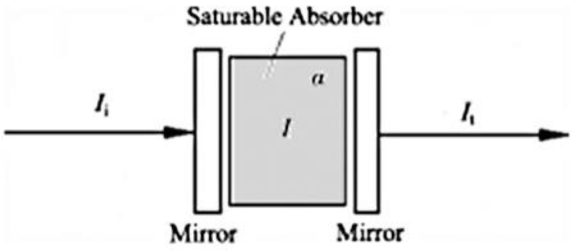


Classification of optical bistable device

Optical Bistable Device

F–P Etalon Absorption Optical Bistable Device

The typical absorption OBD is constituted by placing the saturable absorption medium (absorber) in the F–P resonant cavity, as shown in Figure, where I_i and I_t are incident and transmitted light intensities, respectively, and I is the light intensity in the medium inside the cavity.



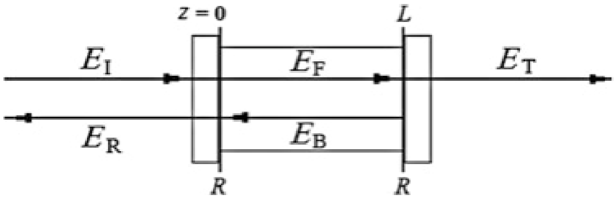
F–P etalon absorption optical bistabledevice

The absorption coefficient of the saturable absorption medium is

$$\alpha = \frac{\alpha_0}{1+(I/I_c)}, \qquad \ldots\ldots\ldots\ldots\ldots \quad 1$$

where α_0 is the linear absorption coefficient; I is the light intensity in the medium; I_c is the saturable intensity. The Eq. (1) shows that the absorption coefficient α decreases with the increase of light intensity I. When the I reaches I_c; $\alpha = \alpha_0/2$.

Assuming the interval between two mirrors of F–P cavity is L, the reflectivity and the transmittance of mirrors are R and T respectively, and the frequency of incident laser is equal to the resonant frequency of F–P cavity.



Light electrical-field distribution in F–P etalon absorption OBD

To denote the incident, reflection, forward, backward and transmitted electric-field amplitude as E_I; E_R; E_F; E_B; E_T respectively, then at $z = 0$, the relationship among these electric-field amplitudes can be expressed as

$$E_F(0) = \sqrt{T}E_I + Re^{-(\alpha/2)2L}E_F(0) = \sqrt{T}E_I + Re^{-\alpha L}E_F(0) \quad \text{……………..} \quad 2$$

Equation (2) can be written to

$$\frac{E_F(0)}{E_I} = \frac{\sqrt{T}}{1 - Re^{-\alpha L}}. \quad \text{………} \quad 3$$

Because $\alpha L << 1$; $e^{-\alpha L} \approx 1 - \alpha L$ and $1 - R = T$, then Eq. (3) can be written to approximately:

$$\frac{E_F(0)}{E_I} \approx \frac{\sqrt{T}}{1 - R(1 - \alpha L)} = \frac{1}{\sqrt{T}(1 + k)}, \quad \text{……..} \quad 4$$

where

$$k \equiv \frac{R\alpha L}{1 - R}. \quad \text{……} \quad 5$$

According to Eq. (1), we have

$$\alpha = \frac{\alpha_0}{1 + I_F/I_c}. \quad \text{……} \quad 6$$

Substituting Eq. (6) into Eq. (5), then we obtain

$$k = \frac{k_0}{1 + I_F/I_c}, \quad \text{……} \quad 7$$

where

$$k_0 = \frac{R\alpha_0 L}{1 - R}. \quad \text{……} \quad 8$$

At $z = L$, the relationship of electric-field amplitudes E_T and E_F is given by

$$E_T = \sqrt{T}E_F(L) = \sqrt{T}e^{-\alpha L/2}E_F(0) \approx \sqrt{T}E_F(0). \qquad \ldots\ldots \quad 9$$

Combing Eqs. (9) and (4), we obtain

$$\frac{E_I}{E_T} = 1 + k. \qquad \ldots\ldots \quad 10$$

Using Eqs. (10) and (7), and $I_T \propto |E_T|^2$; $I_I \propto |E_I|^2$, we obtain

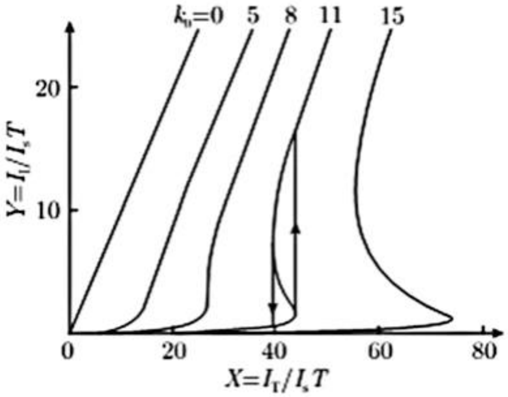
$$\frac{I_I}{I_T} = (1+k)^2 = \left(1 + \frac{k_0}{1 + I_T/TI_c}\right)^2. \qquad \ldots\ldots \quad 11$$

Defining the normalized incident light intensity $X = I_I/TI_c$ and the normalized transmitted light intensity $Y = I_T/TI_c$, Eq. (11) can be written as

$$X = Y\left(1 + \frac{k_0}{1 + Y}\right)^2. \qquad \ldots\ldots \quad 12$$

This is a cubic curve of transmitted light intensity Y; it has the inflection point and the negative slope region, so the system could possess the optical bistability.

Taking different k_0, we can calculate to get a group of relationship curves between the normalized transmitted light intensity and the normalized incident light intensity, i.e., optical bistability curves, as shown in Figure.



Optical bistability curves of F–P etalon absorption OBD under different k_0

From Figure we can see, the condition for generating the optical bistability (or negative slop region) is

$$k_0 \equiv \frac{R\alpha_0 L}{1-R} > 8. \qquad \ldots\ldots \quad 13$$

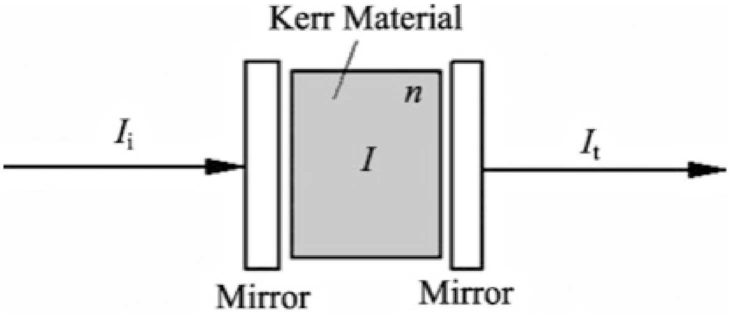
Because 1 – R = T and R ≈ 1, the threshold condition of absorption OB can be express as

$$\frac{\alpha_0 L}{T} > 8. \qquad \ldots\ldots \quad 14$$

Here *T* is transmitted loss of reflective mirror. That is to say, the generation of optical bistability requires the single-trip linear absorption loss of medium in the cavity greater than the transmittance of reflective mirror in eight times.

F–P Etalon Refraction Optical Bistable Device

The typical refraction (dispersion) intrinsic OBD is an F–P etalon filled with an optical Kerr medium, as shown in Figure.



F–P etalon refraction optical bistable device

Setting the incident intensity is I_i, the transmitted intensity is I_t, the intensity inside the medium in the cavity is I, the length of F–P cavity is *L*, and the reflectivity of each mirror is *R*.

For the optical Kerr medium, the refractive index of medium is a linear function of the light intensity:

$$n = n_0 + n_2 I, \qquad \ldots\ldots \quad 1$$

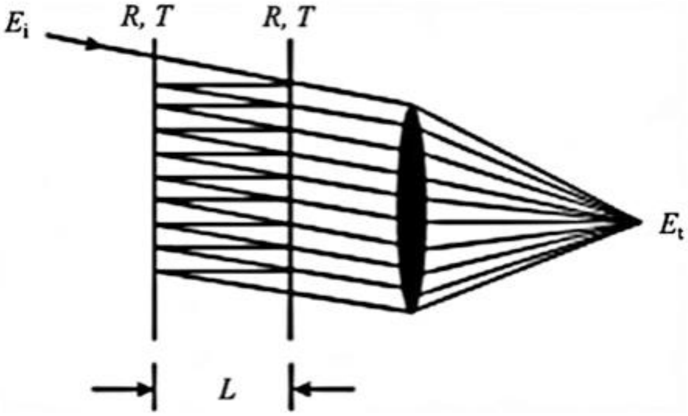
where n_0 is the linear refractive index of medium, n_2 is the nonlinear refraction coefficient. I is light intensity inside the medium in F–P cavity, which can be approximately expressed as

$$I \approx \left(\frac{1+R}{1-R}\right) I_t, \qquad \ldots\ldots \quad 2$$

where I_t is the transmitted light intensity of F–P cavity; R is the reflectivity of the reflective mirror of F–P cavity. Substituting Eq. (1) into Eq. (2), then we obtain

$$n = n_0 + n_2 \left(\frac{1+R}{1-R}\right) I_t. \qquad \ldots\ldots \quad 3$$

The figure plots the optical paths of F–P interferometer based on multi-beam interference.



Schematic diagram of the multi-beam interference for F–P interferometer

Setting the cavity length of F–P interferometer is L, the phase difference between two adjacent transmitted lights, i.e., a round-trip phase shift, which is

$$\phi = \frac{2\pi}{\lambda} n(2L) = \frac{4\pi}{\lambda} nL. \qquad \ldots\ldots \quad 4$$

Substituting Eq. (3) into Eq. (4), we obtain

$$\phi = \phi_0 + \phi_2 I_t, \quad \ldots\ldots \quad 5$$

where ϕ_0 is the light phase shift for a round-trip in the cavity when $I_t \approx 0$ (or the initial phase shift):

$$\phi_0 = \frac{4\pi}{\lambda} n_0 L. \quad \ldots\ldots \quad 6$$

ϕ_2 is a constant related with the nonlinear refraction coefficient n_2:

$$\phi_2 = \frac{4\pi}{\lambda}\left(\frac{1+R}{1-R}\right) n_2 L. \quad \ldots\ldots \quad 7$$

From Eq. (5), the relationship between the transmittance of device τ and the phase shift of light ϕ is

$$\tau = \frac{I_t}{I_i} = \frac{\phi - \phi_0}{\phi_2 I_i}. \quad \ldots\ldots \quad 8$$

Here the relationship of τ and ϕ is a straight line, the slope of straight line is depended on the reciprocal of the incident light intensity. We call Eq. (8) the feedback relation of OB.

Application of Optical Bistable Devices

Optical bistable device has many applications

1- All-optical switches, which will be the basic device for future all-optical systems, for example, all-optical communication and all-optical computer.
2- Light power stabilizer outside the laser cavity (stabilization of optical bistability).
3- Period controllable light pulse generator (instability of optical bistability).
4- Optical flip flop for optical data storage.