

Capacity to generate random signals by semi-nonlinear coupler

Bui Xuan Kien^{1*}, Dinh Van Chau¹, Nguyen Manh Thang², Pham Thanh Quang²

¹Electric Power University;

²Academy of Military Science and Technology.

*Corresponding Email: kienbx@epu.edu.vn

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ABSTRACT

The semi-nonlinear coupler (SNC) is used to split an optical signal into two different amplitude signals, and to reshape a series of signals. The mentioned applications are based on the monotonical dependence of the transmission coefficients on the input intensity, which changes in an interval. In this paper, we show that there is a certain interval of input intensity, in which the transmission coefficients overlap one to other. This behaviors of SNC can be used to generate random signals. Using the expression described the output-input power relation, the expression of the optical merge signal, carrier signal and coded-carrier signal, the overlapping region of the input intensity is numerically observed. Consequence, the random signals are simulated. The obtained signals are discussed to show the opportunity to use them for the information security of the wireless or free-space optical communication in the future.

Keywords: Nonlinear optics; Nonlinear coupler; Optical wireless communication; Free-space communication; Information security.

1. INTRODUCTION

The random and chaotic optical signals are usefull in the random process of electrical and computer processes, computer engineers [1, 2] and communication [3], in which the optical signal is used as the random number [14-19]. There is a lot of random numbers generators: Laser operating under the chaos phase conditions [15-18] as an optical boolean chaos [4, 5]; Based on the dynamics of a semiconductor laser [6-14]; Chaotic laser based physical random bit streaming system with a computer application interface [19]; Generator of random numbers by measuring phase fluctuations from a laser diode with a silicon-on-insulator chip [20]; Real-time optical quantum random number generator based on vacuum fluctuation [21]. Generates a random sequence and transmits optical signal with random-modulated intensity [22]. In the cryptography, an information signal is coded into to the random one to enhance the unditional security [23]. Basing on the phase fluctuation, the real-time optical signal is generated not by the laser under the nonlinear condition only, but by the nonlinear Fabry-Perot [2], one of nonlinear optical devices. The transmission coefficient of the SNC depends on optical intensity [24-27], so it is used not only to split one optical signal into two partial signals in the intensity domain as so as the linear direction coupler [24], but to reshape them in intensity as well as time domain [26]. Moreover, with this feature SNC would be used as the photonic devices can generate nonclassical biphoton states through cascaded quantum walks [28], continuous-variable quantum information processing [29, 30], computation [31], and quantum state engineering [32]. The nonlinearity of SNC using organic dye is very high [33, 34], so the above feature can be significantly enhanced. We hope mentioned feature will appear for SNC.

In this paper we propose a SNC designed from two rods, one of them is the dry organic dye solution and another is dry solvent. Next, the expressions describing the output-input power relation is introduced. Last, the random optical signal at output port is numerically simulated using an assumed coded-carrier optical signal at input port. The overlapping region of input power suitable to conFigureuration of SNC to generate the random optical signal, and the

opportunity use in information security are discussed.

2. PROBLEM

2.1. Model of SNC

A model of SNC is proposed and presented in Figure 1. In this paper we propose to use a dry organic dye solution rod as nonlinear branch to enhance the nonlinearity [22, 28], while the another is used dry solvent only. The input laser signal is injected into nonlinear branch at input-port, the output laser signals are generated from both branches at through-port and cross-port, respectively.

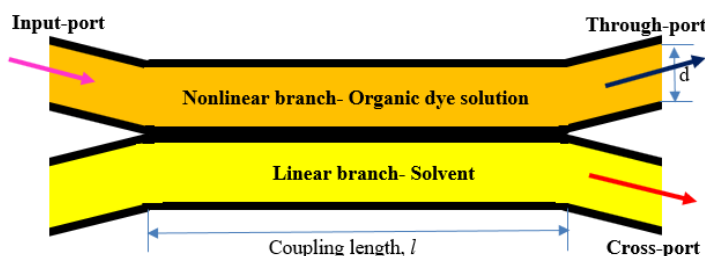


Figure 1. Sketch of SNC.

2.2. Output-input relation of powers

Using the superposition principle, the optical field propagating inside every branch is written as following [35, 37]:

$$E(x, y, z, t) = \sum_i A_i(z) F_i(x, y) \exp[i(\omega_i t - \beta_i z)] \quad (1)$$

where $A_i(z)$ is the amplitude, $F_i(x, y)$ is the spatial harmonic function, ω_i is the frequency and β_i is the propagation constant of i^{th} field.

The refractive index of both branches can be written as following:

$$\begin{aligned} n_1^2(x, y) &= n_{c1}^2(x, y) + n_{o1}^2(x, y) + n_{nl}^2(x, y) |E(x, y)|^4 \\ n_2^2(x, y) &= n_{c2}^2(x, y) + n_{o2}^2(x, y) \end{aligned} \quad (2)$$

where $n_{ci}(x, y) = n_c$ is the refractive index of rod's clad, $n_{oi}(x, y)$ is the linear refractive index of solution and solvent and $n_{nl}(x, y)$ is the nonlinear coefficient of refractive index of organic dye. Two field propagating through SNC satisfy the Helmholtz equation [35]:

$$\nabla^2 E + n^2(x, y) k_0^2 E = 0 \quad (3)$$

where $k_0 = \omega/c$ is the wavenumber. The function $F_i(x, y)$ and amplitude $A_i(z)$ can be solved from Eq. (3). Substituting Eq.(1) into Eq. (3) we obtain equation of the function $F_i(x, y)$

$$\frac{\partial^2 F_i(x, y)}{\partial x^2} + \frac{\partial^2 F_i(x, y)}{\partial y^2} - [\beta_i^2 - n_i^2(x, y) k_0^2] F_i(x, y) = 0 \quad (4)$$

Using the slowly varying approximation, we obtain two coupled first-order differential equations that govern the variation of the amplitudes $A_i(z)$ [36]:

$$\begin{aligned} \frac{dA_1(z)}{dz} &= iC_{11}A_1(z) - iC_{nl}A_1(z) - iC_{12}A_2(z) \exp[i(\beta_1 - \beta_2)z] \\ \frac{dA_2(z)}{dz} &= iC_{22}A_2(z) - iC_{21}A_1(z) \exp[-i(\beta_1 - \beta_2)z] \end{aligned} \quad (5)$$

where C_{ij} are the linear coupling coefficient, C_{nl} is the nonlinear coupling coefficient, which are given as following:

$$\begin{aligned} C_{ij} &= \frac{\omega \varepsilon_0}{4} \iint F_i^*(x, y) n_{0i}^2(x, y) F_j(x, y) dx dy ; \\ C_{ii} &= \frac{\omega \varepsilon_0}{4} \iint F_i^*(x, y) n_{0j}^2(x, y) F_i(x, y) dx dy ; \\ C_{nl} &= \frac{\omega \varepsilon_0}{4} \iint F_i^*(x, y) n_{nl}^2(x, y) |E_i(x, y)|^4 F_i(x, y) dx dy . \end{aligned}$$

Coupling can be regarded as a scattering effect. The field of linear branch is scattered from nonlinear branch, creating a source of light that changes the amplitude of the field in nonlinear branch. The field of linear branch has a similar effect on nonlinear branch. We assume that the linear refractive indices of both branches are same, and then the linear coupling between branches is equivalent, so $C_{11} = C_{22} = C_{12} = C_{21} = C = const$ [27]. After some arrangements the expressions of output powers from through-port, P_{th-p} and cross-port P_{cr-p} are given as following:

$$\begin{aligned} P_{th-p}(l) &= P_{in} \left[1 - \frac{C^2}{C_{nl}^2 + C^2} \sin^2 \left(l \sqrt{C_{nl}^2 + C^2} \right) \right] \\ P_{cr-p}(l) &= P_{in} \frac{C^2}{C_{nl}^2 + C^2} \sin^2 \left(l \sqrt{C_{nl}^2 + C^2} \right) \end{aligned} \quad (6)$$

where C_{nl} is the nonlinear coupling coefficient which is given as following:

$$C_{nl} = \frac{16c\varepsilon_0 n_{nl}^2 P_{in}^2}{\pi \lambda d^4} \quad (7)$$

where, λ and c are the frequency and velocity of light, ε_0 is the permittivity constant of vacuum, n_{nl} is the nonlinear coefficient of refractive index, $P_{in} \equiv P_{in}(0) = I_{in}(0) \pi d^2 / 4$, $P_{th-p}(l)$, $P_{cr-p}(l)$ are powers at input port, through-port and cross-port, respectively, d is rod's diameter, and l is the coupling length (see figure 1).

Here, let us to discuss about the competition of the nonlinear and linear couplings: i) If $n_{nl} = 0$,i.e., $C_{nl} = 0$, Eq (6) will be used for the linear coupler in which the transmission depends on the coupling length and linear coupling coefficient; The transmission coefficient has determined value relating to given coupling length, and then SNC operates as an optical splitter; ii) If $n_{nl} \neq 0$ and P_{in} is high enough so that $C_{nl} \gg C$, $P_{cr-p} \rightarrow 0$ and $P_{th-p} \rightarrow P_{in}$, then SNC operates as an optical straightforward transmitter; iii) If $C_{nl} \sim C$ there is a competition between the nonlinear and linear couplings, which depends mainly on the input power and then SNC operates as an optical signal shaper with own nonlinear feature. This feature will be attracted if the organic dye with high nonlinearity is used, hence, the weak optical signal can be used. In this paper we focus attention on this cases, specially when the input power oscillates as an optical modulated signal.

Now we guess that an optical message signal given as following:

$$P_{sgn} = P_{0,sgn} m(t) \sin \left(\frac{2\pi t}{T_{sgn}} \right) \quad (8)$$

where $P_{0,sgn}$ is the amplitude, $m(t)$ is the modulating depth varying in the real time t , T_{sgn} is the period. This signal will be transmitted by the optical carrier signal, which is given as:

$$P_{\text{carr}} = P_{0,\text{carr}} \left(2 + A \sin \left(\frac{2\pi t}{T_{\text{carr}}} \right) \right) \quad (9)$$

where $P_{0,\text{carr}}$ is the amplitude, T_{carr} is the period shorter than the period of the message signal T_{sgn} ($T_{\text{carr}} \ll T_{\text{sgn}}$), A is the parameter to control the oscillation depth. From (8) and (9), we assume the carrier signal modulated by the ways described following:

$$P_{\text{cod}} = P_{0,\text{carr}} \left[2 + A \sin \left(\frac{2\pi t}{T_{\text{carr}}} \right) \right] + P_{0,\text{sgn}} m(t) \sin \left(\frac{2\pi t}{T_{\text{sgn}}} \right) \quad (10)$$

which is “called” the optical coded-carrier signal. Substituting Eq. (10) into Eq.(6) we can obtain two “random” optical signals at the output ports of SNC with suitable collection of given parameters. Our guess will be confirmed by numerical calculation in the next section.

3. RESULTS AND DISCUSSION

3.1. Output-input characteristics of powers

Now we numerically calculation the output-input characteristics of power of lights propagating through the SNC. We consider a SNC is designed from two parallel rods having diameter of $10 \mu\text{m}$, which is seem as the single mode fiber. The nonlinear branch is the dry organic dye solution and another one is the dry solvent. The nonlinear coefficient of organic dye is be chosen $n_{nl}=2.10^{-6} \text{ cm}^2/\text{W}$ and $4.10^{-6} \text{ cm}^2/\text{W}$ [33, 38] for two interesting cases. The coupling length of SNC is 9 cm . The input light is the laser with wavelength of $1.55 \mu\text{m}$ and power changed from 85 dBm to 120 dBm . For simplicity, the linear coupling C is approximately chosen to be $\sim 1.10^{-3} \text{ rad}^2/\text{mm}$ as so as that of the polymer fibers [37, 38].

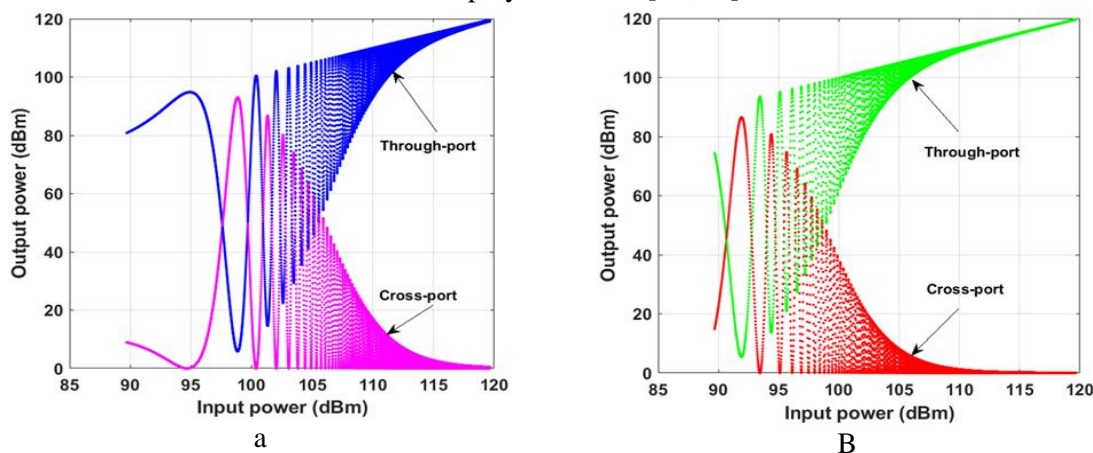


Figure 2. Output powers at through-port and cross-port vs. input power for two cases: $n_{nl}=2.10^{-6} \text{ cm}^2/\text{W}$ (a) and $4.10^{-6} \text{ cm}^2/\text{W}$ (b).

Firstly, using Eq. (6) and Eq. (7) we calculate the output powers transmitted from the designed SNC. For the case of $n_{nl}=2.10^{-6} \text{ cm}^2/\text{W}$ the calculated results are presented in figure 2a. We can see that the output powers at both output ports oscillation depends on the input power, but not depending on its orientation. If the input power increases to 97 dBm , the output powers are distinguished till read equivalence. If the input power is higher 106 dBm , after reaching equivalence the output power at through-port increases to equal input power, while one at cross-port decreases to zero. Specially, in the region $(97 \div 106) \text{ dBm}$ of input intensity the output powers at both ports oscillate and overlap. This region of the input power can be changed if the organic dye changes with different nonlinear coefficient of refractive index (can see in figure 2b). This

power region is called as “overlapping” region of input intensity in the SNC.

3.2. Generation of random optical signals

First, we reconfirm that, the overlapping and oscillating of two output powers will appear when the input signal oscillates in the overlapping region. So for simulation we chose $I_{0,carr} = 4.7 \times 10^3 \text{ W/cm}^2$, $A = 0.2$, $T_{carr} = 5 \text{ a.u.}$ for carrier signal; $I_{0,sgn} = 1 \times 10^2 \text{ W/cm}^2$, $T_{sgn} = 4T_{carr} = 20 \text{ a.u.}$,

$m(t) = 0.2 \left(\lfloor t/T_{sgn} \rfloor + 1 \right)$ for message signal.

All signals described in Eq. (8), (9) and (10) are calculated and shown in figure 3. The carrier signal (figure 3a) can be used as a semiconductor laser pulse, the simulated message signal (figure 3b) can be used as the radio signal or sound signal and the coded-carrier signal (figure 3c) can be used as the continuous-variable laser beam transmitting to the receiver [39]. It is clear that the coded-carrier signal having power oscillates from 87 dBm to 101 dBm, which is in the overlapping region.

Substituting Eq. (10) to Eq. (6), and using collection of given parameters to Eq. (7), we numerically resolve and obtain results illustrated in figure 4. It shows that, the attitude of two output signals are quite different to that of coded-carrier signal. They oscillate randomly in every period, and period after period. Specially, almost of output signals has the stable maximum level of power, it is seem not changed period after period. This feature makes the output signals are completely different to the coded-carrier signal. Moreover, if the nonlinearity of SNC is higher (figure 4b and 4d) the output signals oscillate increase, i.e., the random degree is higher. It is important that the output signals oscillate randomly in time, i.e., their power change at every time, however, the conservation of their powers is always satisfied.

From above obtained results, it is clear that the optical random signals can be generated by SNC for an optical message signal with suitable coded-carrier signal having power oscillating in the overlapping region. Their amplitude and attitude depend not only on the amplitude and period of the coded-carrier signals, but on the nonlinearity of SNC. The quite distinct of the random signals to coded-carrier signal makes it can be used as a coded light pulse [39, 40] for the encode key information or encrypt key information [23, 41]. The random behavior of optical output signals generated by SNC, and the transmission skill (for example: send them with certain delay time) are the facts to enhance the information security for optical fiber communication [42-

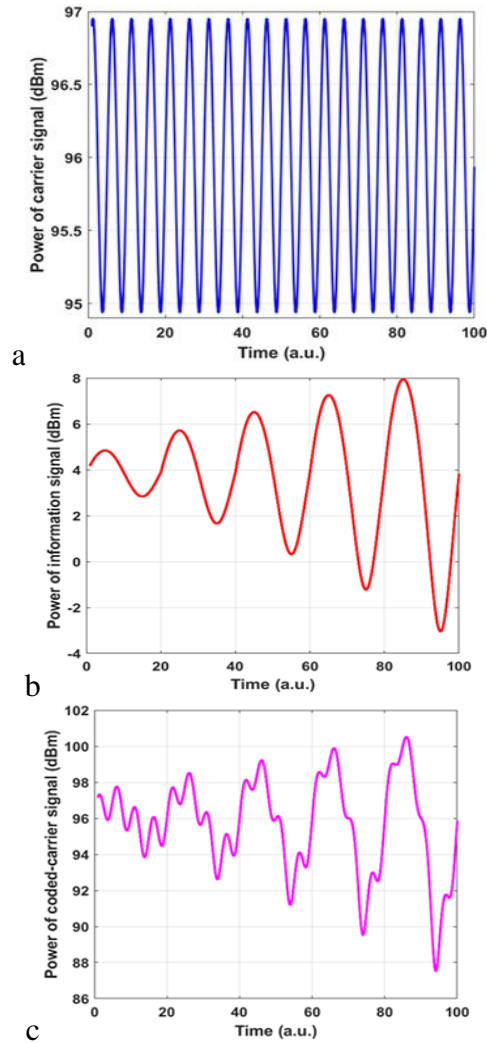


Figure 3. Carrier signal (a), information signal (b) and coded-carrier signal (c).

44], specially, the unconditional security for wireless optical communication [45-47]. Particularly, the known optical coded-carrier signal modulated by the message signal would be split into two optical random signals, which could be unknown for the stranger, from through-port and cross-port of SNC, and then they are individually transferred with delay time to receiver of Alice and Bob as so as the time-bin entanglement. The decoding method to know original message signal will be corresponded between Alice and Bob through classical channel [48].

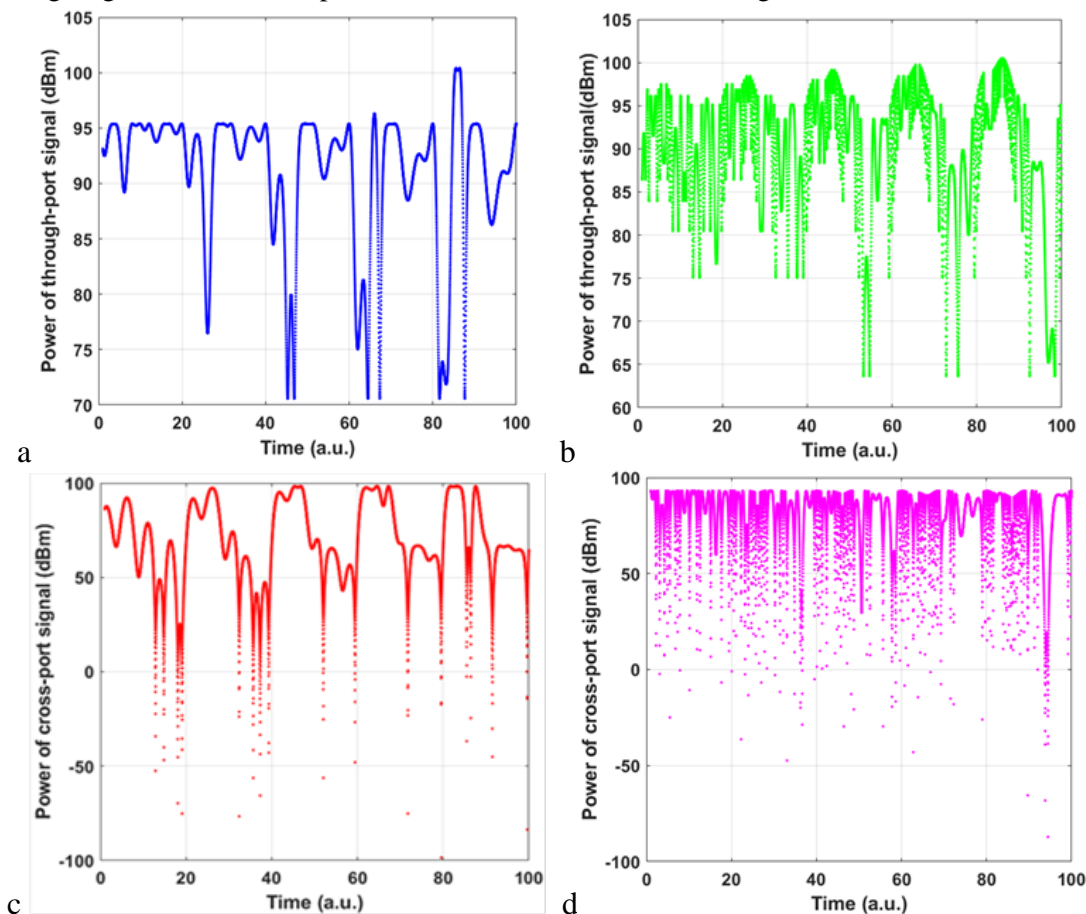


Figure 4. Random signals from SNC at through-port (a, b) and cross-port (c, d) for two interesting cases: $n_{nl}=2.10^{-6} \text{ cm}^2/\text{W}$ (a, c) and $4.10^{-6} \text{ cm}^2/\text{W}$ (b, d).

4. CONCLUSIONS

We have proposed SNC designed from dry organic dye solution rod and its dry solvent rod. The expressions describing the power relation propagating inside SNC are presented. Using data closed to experiment, the output-input power characteristics are numerically simulated and the overlapping region of power, in which appears the competition of linear and nonlinear couplings, is discussed. The generation of the random signals is also simulated using assumed message, carrier, and coded-carrier signals. We obtain the output signal generated from SNC having attitude quite different to the coded-carrier signal. This feature of random signals gives us an opportunity to use them for the information security in the fiber communication, specially, in the free-space communication. In this paper we limit our investigation in one simple model of SNC and signals with the purpose to show a remarkable behavior of SNC. There is a lot of problems as the signal modulation method [49], the system of SNCs for multichannel generation of random signal, SNC owning different overlapping region of power will be investigated in the

next papers. This feature of proposed SNC is hint to design the real-time random optical signal generator in the future.

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TÓM TẮT

Tạo tín hiệu ngẫu nhiên bằng bộ liên kết bán phi tuyến

Bộ liên kết bán phi tuyến (SNC) được sử dụng để tách tín hiệu quang thành hai tín hiệu có biên độ khác nhau và định hình lại một loạt tín hiệu. Các ứng dụng được đề cập dựa trên sự phụ thuộc đơn điệu của các hệ số truyền vào cường độ đầu vào, thay đổi trong một khoảng thời gian. Trong bài báo này, chúng tôi chỉ ra rằng có một khoảng cường độ đầu vào nhất định, trong đó các hệ số truyền tải trùng nhau. Những đặc điểm này của SNC có thể được sử dụng để tạo tín hiệu ngẫu nhiên. Sử dụng biểu thức mô tả mối quan hệ công suất đầu ra-đầu vào, biểu thức của tín hiệu trộn lẫn quang học, tín hiệu sóng mang và tín hiệu sóng mang được mã hóa, vùng chồng lấn của cường độ đầu vào được quan sát bằng số. Do đó, các tín hiệu ngẫu nhiên được mô phỏng. Các tín hiệu thu được sẽ được thảo luận để chỉ ra cơ hội sử dụng chúng cho bảo mật thông tin của truyền thông quang không dây hoặc không gian tự do trong tương lai.

Từ khóa: Quang học phi tuyến; Bộ ghép phi tuyến; Thông tin quang không dây; Thông tin trong không gian tự do; Bảo mật thông tin.