

NOVEL NANO-ANTENNA SYSTEM DESIGN USING PHOTONIC SPIN IN A PANDA RING RESONATOR

N. Thammawongsa^{1,2}, N. Moongfangklang³, S. Mitatha¹,
and P. P. Yupapin^{4,*}

¹Hybrid Computing Research Laboratory, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520,
Thailand

²Department of Electronics Engineering, Faculty of Technology,
Udonthani Rajabhat University, Udonthani 41000, Thailand

³Schools of Information and Communication Technology, Phayao
University, Phayao 56000, Thailand

⁴Nanoscale Science and Engineering Research Alliance (N'SERA), Fac-
ulty of Science, King Mongkut's Institute of Technology Ladkrabang,
Bangkok 10520, Thailand

Abstract—A novel nano-antenna system design using photonic spin in a PANDA ring resonator is proposed. This photonic spins are generated by a soliton pulse within a PANDA ring, in which the transverse electric (TE) and a transverse magnetic (TM) fields are generated. The magnetic field is introduced by using an aluminum plate coupling to the microring resonator, in which the spin-up and spin-down states are induced, where finally, the photonic dipoles are formed. In operation, the dipole oscillation frequency is controlled by a soliton power, coupling coefficients, and ring radii. The obtained results have shown that THz frequency source can be generated by the proposed system. The advantage of proposed system is that the simple and compact nano-antenna with high power pulse source can be fabricated, which can generate and detect the THz frequency in a single system.

1. INTRODUCTION

Nanoscale devices have played a crucial role in the nanoscopic regime, especially, in information technology. One of the objectives is the

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* Corresponding author: Preecha P. Yupapin (kypreech@kmitl.ac.th).

searching of small device for telephone handset, which is always a challenge. One of the key devices of the telephone handset is an antenna. Therefore, the searching of a small antenna with good performance is necessary, in which a new type of a nano-antenna is recommended for the modern telephone handset application. To date, nano-antenna has become an interesting field as seen from many aspects of applications such as biology and medicine [1], monitoring and spectroscopy, medical imaging [2,3], security [3], material spectroscopy and sensing [4], and high data rate communications [5]. For the high frequency in THz scale, optical nano-antenna offers dominant feature of a micro/nanoscale device. Moreover, it has potential advantages in the detection of light showing polarization, tunable, and rapid time response. Another challenge is high loss at optical frequency that becomes the limitation ability to extend current at the optical spectrum.

A variety of ideas for using submicron devices have been proposed. Firstly, converting solar radiation to electricity was proposed by Bailey in 1973 [6], then sub-micron-antenna for the direct light power converted to electrical power by Alvin in 1984 [7]. Lin et al. first proposed resonant light absorption by a fabricated nanostructure and rectification of light with frequency in the visible range in 1996 [8], which opened the new era of nano-antenna. Over the past few years, several researches have performed in nano-antenna. For instance, dipole antenna was described by a simple antenna frequency radiation and characteristics [9]. Next, monopole antenna was used for nanometer resolution optical microscopy [10]. Then, a nanorod antenna using surface plasmon theory to improve the surface enhanced Raman spectroscopy was reported [11]. And several types of 'gap' antenna provide a definitive understanding of a new antenna electromagnetic surface which can be used to optimize antenna performance [12]. All of these antennas demonstrate approximately a dipolar angular emission, that their modes both radiated and excited with a dipolar angular dependence. Recently, bowtie antenna has been used as near-field probes and nanolithography [13]. An optical Yagi-Uda nano-antenna was proposed in [14] with near-field coupling used to feed the element at the resonance frequency. The surface plasmon resonance behavior [15, 16] has an interesting principle effect which determines angular emission performance of the coupled system and improves efficiency at selected frequency. Gold nanoparticles are most widely used as nano-antenna because they have controllable size distribution, long-term stability, high homogeneity, and they also exhibit plasmon resonances in the visible spectrum [17].

Photonic (optical) spin has become a very popular field nowadays;

there are enormous applications of optical spin [18], such as long distance optical transport, communication network and security, quantum computer, and communication. Besides, spin mechanism using bright and dark soliton conversion behaviors was demonstrated by Yupapin et al. [19,20], which consists of an add-drop optical filter known as a PANDA ring resonator. Soliton spin can be decomposed into left and right circularly polarized waves called “a dark-bright soliton pair” that can be used to generate the orthogonal set of axes (TE and TM modes), in which finally, the dipole oscillation can be established. Although there are many investigations of nano-antenna and optical spin, the complete information about nano-antenna using optical spin is unavailable. Therefore, this paper proposes a method that accommodates between nano-antenna design and optical spin manipulation by using a PANDA ring resonator. The obtained results show the spin mechanism using bright and dark soliton conversion to increase the efficiency of optical nano-antenna radiation and current emission. Furthermore, the proposed system can also be used for wide range of applications, such as nano-sensor, biomedicine, high data rate communication system, and spectroscopy.

2. PHOTONIC DIPOLE

The simple way to understand the origin of various optical effects in many substances is based on optical dipole interaction model, where photon from source can result in serious effect when the light is interacting in structure at nanoscale. Polarization plays the role of

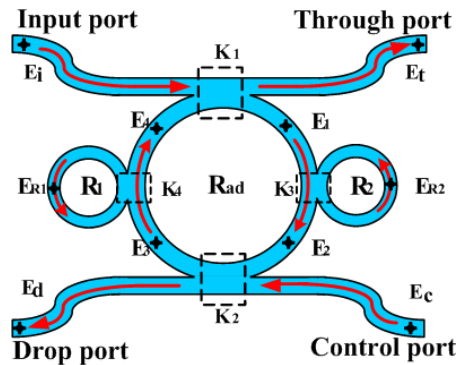


Figure 1. A schematic diagram of a PANDA ring resonator, where R_i : ring radii, E_i : electric fields, κ_i : coupling coefficients, input field, through port, drop port, and control port.

the absorption cross section of a nano-antenna in which the radiation induces dipole in the atom and intensity gradient. Optical dipole is formed by spin manipulation [21], in which the orthogonal solitons can be formed within the system at the output ports. Under the resonant condition, the dark and bright soliton pair corresponding to the left-hand and right-hand rotating solitons (photons) can be generated. When a soliton is absorbed by an object, an angular momentum of either $+\hbar$ or $-\hbar$ is imparted to the object, in which two possible spin states are exhibited. In the proposed system, the PANDA ring resonator was used to form the orthogonal set of dark-bright soliton pair, which can be decomposed into right and left circularly polarized waves as shown in Fig. 1. The relative phase of the two output light signals after coupling into the optical coupler is $\pi/2$. This means that the signals coupled into the drop port (*Dr*) and through port (*Th*) have acquired a phase of π with respect to the input port (*In*) signal. The input and control fields at the input port and control port (*Ct*) are formed by the dark and bright optical solitons as described by Equations (1) and (2).

$$E_{in}(t) = A_0 \tanh \left[\frac{T}{T_0} \right] e^{\left(\frac{z}{2L_D} \right) - i\omega_0 t} \quad (1)$$

$$E_{in}(t) = A_0 \operatorname{sech} \left[\frac{T}{T_0} \right] e^{\left(\frac{z}{2L_D} \right) - i\omega_0 t} \quad (2)$$

Here A_0 and z are the optical field amplitude and propagation distance, respectively. $T = t - \beta_1 z$, where β_1 and β_2 are the coefficients of the linear and second-order terms of Taylor expansion of the propagation constant. $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. T_0 in equation is a soliton pulse propagation time at initial input, where t is the soliton phase shift time, and the frequency shift of the soliton is ω_0 . The optical fields of the system in Fig. 1 are obtained and expressed in the following forms.

$$E_1 = -j\kappa_1 E_i + \tau_1 E_4, \quad (3)$$

$$E_2 = E_1 e^{(j\omega T/2)} e^{(-\alpha L/4)}, \quad (4)$$

$$E_3 = \tau_2 E_2 - j\kappa_2 E_c, \quad (5)$$

$$E_4 = E_3 e^{(j\omega T/2)} e^{(-\alpha L/4)}, \quad (6)$$

$$E_t = \tau_1 E_i - j\kappa_1 E_4, \quad (7)$$

$$E_d = \tau_2 E_a - j\kappa_2 E_2, \quad (8)$$

Here E_i is the input field, E_c the control field, E_t the through field, E_d the drop field, E_1 , E_2 , E_3 and E_4 the fields in the Ring, κ_1 the field coupling coefficient between the input bus and ring, κ_2

the field coupling coefficient between the ring and output bus, L the circumference of the ring, T the time taken for one round trip (roundtrip time), and α the power loss in the ring per unit length. We assume that this is the lossless coupling, i.e., $\tau_{1,2} = \sqrt{1 - \kappa_{1,2}^2}$. $T = Ln_{eff}/c$.

The output power/intensities at the drop and through ports are given by

$$|E_d|^2 = \left| \frac{-\kappa_1 \kappa_2 A_{1/2} \Phi_{1/2}}{1 - \tau_1 \tau_2 A \Phi} E_i + \frac{\tau_2 - \tau_1 A \Phi}{1 - \tau_1 \tau_2 A \Phi} E_a \right|^2. \quad (9)$$

$$|E_t|^2 = \left| \frac{\tau_2 - \tau_1 A \Phi}{1 - \tau_1 \tau_2 A \Phi} E_i + \frac{-\kappa_1 \kappa_2 A_{1/2} \Phi_{1/2}}{1 - \tau_1 \tau_2 A \Phi} E_a \right|^2. \quad (10)$$

Here $A_{1/2} = \exp(-\alpha L/4)$ (the half-round-trip amplitude), $A = A_{1/2}^2$, $\Phi_{1/2} = \exp(j\omega T/2)$ (the half-round-trip phase contribution), and $\Phi = \Phi_{1/2}^2$.

In operation, the orthogonal soliton sets can be generated by using the system as shown in Fig. 2. The optical field is fed into the ring resonator system, where $R_1 = R_2 = 2.5 \mu\text{m}$, $R_{ad} = 30 \mu\text{m}$ by using a microring, $R_{Th} = R_{Ct} = 20 \mu\text{m}$. To form the initial spin states, the magnetic field is induced by an aluminum plate coupled on AlGaAs waveguides for optoelectronic spin-up and spin-down states. The coupling coefficient ratios k_1 , k_2 , k_3 and k_4 are 10:90, 10:90, 20:80 and 20:80 acting in the following manners: (a) dark soliton is input into input and control ports, (b) dark and bright solitons are fed for input and control signals, (c) bright and dark solitons are used for input and control signals, and (d) bright soliton is used for input

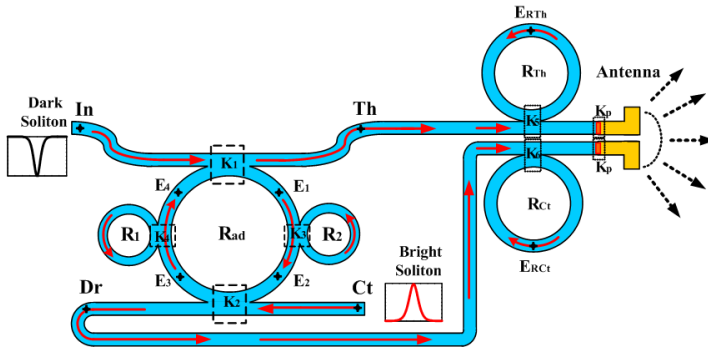


Figure 2. Schematic of optical nano-antenna by optical spin manipulation generated within a PANDA ring resonator.

and control signals. The ring radii $R_{ad} = 30 \mu\text{m}$, $A_{eff} = 0.25 \mu\text{m}^2$, $n_{eff} = 3.14$ (for InGaAsP/InP) [21, 22], $\alpha = 0.1 \text{ dB/mm}$, $\gamma = 0.01$, $\lambda_0 = 1.55 \mu\text{m}$. Fig. 3 shows the output intensities for spin-injected for transverse electric (TE), and transverse magnetic (TM) fields are generated by using a PANDA ring resonator. The optoelectronic fields are generated by a dark-soliton pump based-on through port and drop port microring resonator at center wavelength $1.45 \mu\text{m}$. In Figs. 3 and 4, simulation results are obtained by using commercial MATLAB software and OPTIWAVE [23]. However, all parameters have been chosen closely to the practical parameters, which means that the device can be fabricated [19–22]. Many soliton spins are detected at through (spin up) and drop (spin down) ports of a PANDA ring resonator in Fig. 3. The optoelectronic spin manipulation generated within a PANDA ring resonator is as shown, where the output signals are

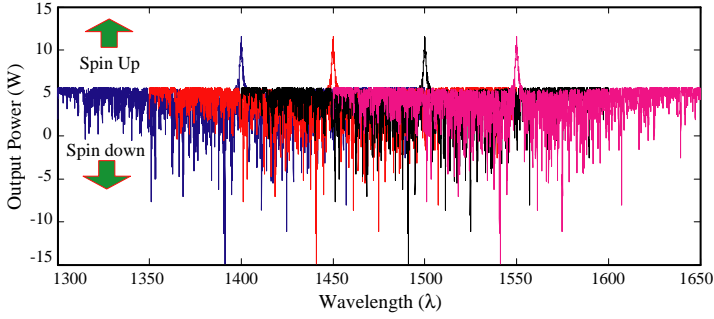


Figure 3. Many soliton spins are detected at through (spin up) and drop (spin down) ports.

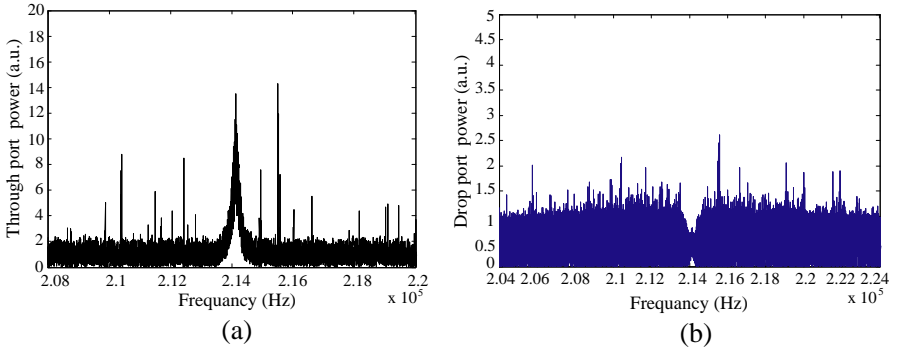


Figure 4. Output frequencies generated at through port and drop port, where (a) through port, (b) drop port.

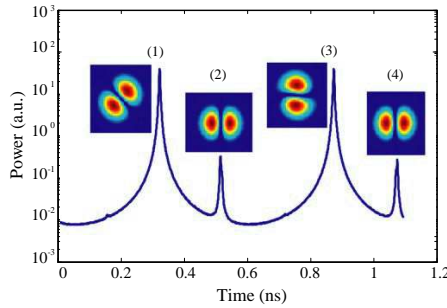


Figure 5. Photonic dipole oscillation generated within a PANDA ring resonator, where (1), (2), (3) and (4) present the different positions during oscillation within a PANDA ring [21].

randomly obtained at the *Th* and *Dr* ports as illustrated in Figs. 4 and 5, in which the random TE and TM fields of the solitons corresponding to the left-hand and right hand photons can be generated and detected. The angular momentum of either $+\hbar$ or $-\hbar$ is imparted to the object when a photon is absorbed by an object, where two possible spin states known as optoelectronic spins are exhibited.

3. NANO-ANTENNA MANIPULATION

Nano-antenna differs from radio frequency antenna in two important aspects; first, due to high losses at optical frequencies at which the assumption of perfect electrical conductor is no longer valid and second due to unique phenomena at nanoscale (surface plasmon polarization). The most important different response of these structures is the sub wavelength field confinement. Therefore, serious efforts have been devoted to extend current understanding from radio frequency antennas to their nano-antenna counterparts. The model of an infinitesimal dipole to discuss the different characters of the fields in near-field and far-field regions is used. This model further helps to appreciate the difference between the radiated power and the power stored in the near-field of an antenna. The nano-antenna system is as shown in Fig. 6, which is used to find the optimum dipole antenna half wavelength for transmission. Actually, the waveguide dimension in the nanoscale regime is about 200–700 nm [21], and an electron can be trapped within a 0.22 nm [24]. However, in our proposed system, an electron is not induced within the antenna, i.e., it is a photon. An electron is induced and propagated in the medium outside the antenna.

By using the proposed system, the current density, dipole

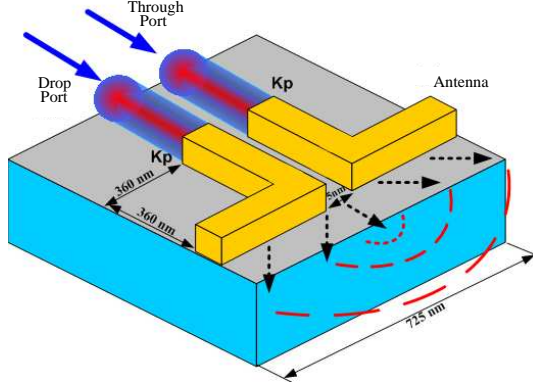


Figure 6. A nano-antenna system using optical spin.

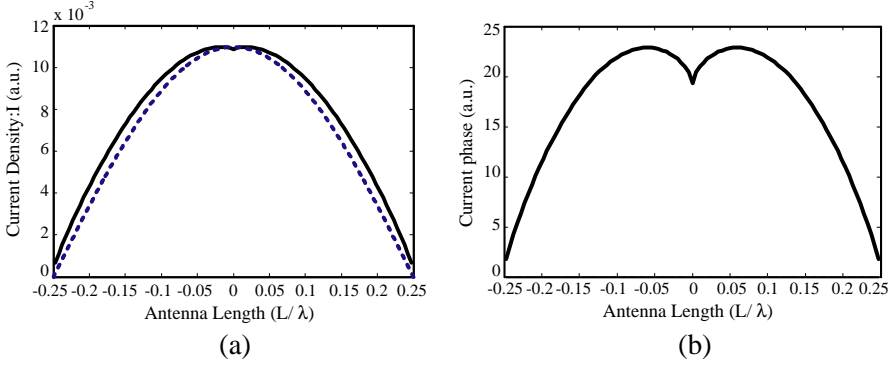


Figure 7. (a) Current density and (b) current phase of nano-antenna.

radiation and field enhancement behavior are calculated as shown in Fig. 7. The sinusoidal current distribution (I_s) is given by [25] from Equation (11), where I_m is the current amplitude, L the total antenna length ($\lambda/2$), a the radius of the wire ($1/500$), and k_0 the wave vector. This first approximation is very useful for calculating the radiation patterns for antenna length L , in which the highest current density and phase are obtained.

$$I_s(z) = I_m \sin \left(k_0 \left(\frac{1}{2}L - |z| \right) \right) \quad (11)$$

To analyze the dipole antenna in more details, a realistic current density of a dipole antenna is obtained using Pocklington's integral equation [26]. The calculation of the complex one-dimensional current density was performed by using the MATLAB functions which

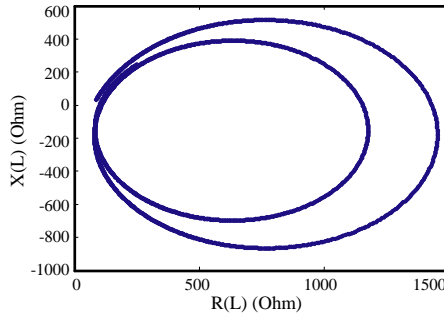


Figure 8. Impedance of nano-antenna (L/a).

fabricated based on reference [27]. The antenna input impedance is defined in [28]. The simplify impedance of antenna for transmitted and received power at different lengths was calculated. The input impedance for a design dipole nano-antenna with a length-to-radius ratio L/a is shown in Fig. 8.

The performance of optical spin from PANDA ring resonator is a factor to improve the optical intensity for feeding into nano-antenna. The most popular nano-antenna material is gold that gives a good effect of resonance and dielectric constant values. The optical properties of gold following a Drude model in this work are consistent with the data in [29]. The dispersion relation of the surface plasmon resonance at the interface is given by [30].

$$k_p = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_d(\omega)}{\varepsilon_d + \varepsilon_d(\omega)}} \quad (12)$$

Here k_0 is the wave vector in air, ε_d the relative permittivity of the dielectric, and $\varepsilon_m(\omega)$ the dispersive relative permittivity of the metal. The total complex average power delivered to the antenna is demonstrated in Equation (13) which analyzes the power radiated in an infinitesimal dipole.

$$P = \frac{1}{2} |I_g|^2 Z_a = \frac{|V_g^2|}{2} \frac{R_a + X_a}{(R_a + R_g)^2 + (X_a + X_g)^2} = P_r + iP_{reac} \quad (13)$$

From above equation, the imaginary part of P can be assigned to the reactive power P_{reac} , stored in the reactive near-field. This time, P_{reac} represents the total reactive power. The real part of P is usually in addition to the radiate power P_r , Z_a the antenna impedance, and I_g and V_g the source current and voltage, respectively.

In order to estimate the field in a gold nano-antenna gap, the electric field component is the field inside capacitor, in which the

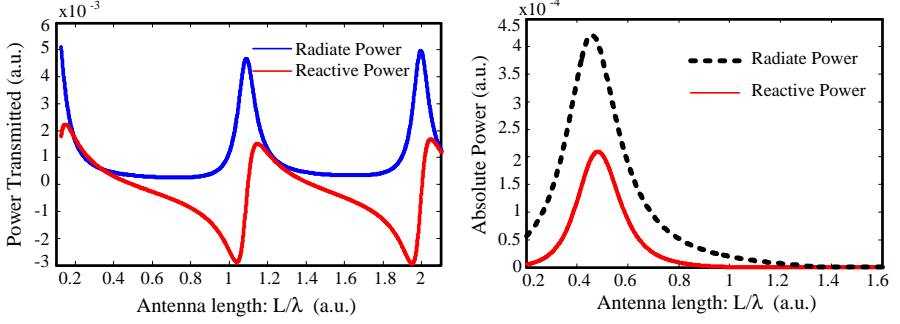


Figure 9. Power transmission of Nano-antenna (L/a).

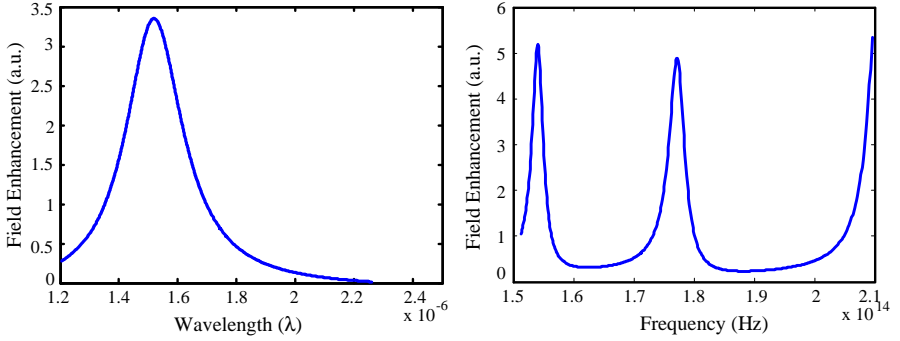


Figure 10. Nano-antenna field enhancement compared with wavelength and frequency.

incident field is given by Pocklington's integral equation [26]. The intensity enhancement in the feed-gap as a function of the total antenna length for a dipole antenna was described by [31]. The power radiation and field enhancement are illustrated in Figs. 9 and 10, where the transmitted power from the antenna and normalized field enhancement are compared to the wavelength and frequency domains. In addition, the antenna impedance is affected by the antenna gap. This design results present the optical spin method that generates frequency and radiates using nano-antenna, which is a simple model. The optical high power source initiating the highest surface plasmon resonance is vital to generate optical intensity and polarization.

4. CONCLUSION

This paper proposes an interesting system and technique that can be used to form the nano-antenna. By using the photonic spin, the

photonic dipole and dipole oscillation can be established, which is available for antenna application. Results have shown that the THz frequency generated by the two optical dipole components (TE and TM waves) of polarized light can form the orthogonal soliton pair within a PANDA ring resonator. The output signals of Th and Dr ports can form the photonic spin-up and spin-down states which are available for wide range nano-antenna frequency oscillation. Furthermore, our simple method can be applied to several nano-antenna designs by using optical spin manipulation technique leading to a novel guideline to develop in wireless nanoscale device communication. In addition, optical dipole can be used for further investigations such as dynamic dipole, dynamic torque, nano-motor, spin communication and spin cryptography, etc.

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