High-Efficiency Resonant Beam Charging and Communication

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Abstract—With the development of Internet of Things (IoT), demands of power and data for IoT devices increase drastically. In order to resolve the supply-demand contradiction, simultaneous wireless information and power transfer (SWIPT) has been envisioned as an enabling technology by providing high-power energy transfer and high-rate data delivering concurrently. In this paper, we introduce a high-efficiency resonant beam (RB) charging and communication scheme. The scheme utilizes the semiconductor materials as gain medium, which has a better energy absorption capacity compared with the traditional solid-state one. Moreover, the telescope internal modulator (TIM) are adopted in the scheme which can concentrate beams to match the gain size, reducing the transmission loss. To evaluate the scheme SWIPT performance, we establish an analytical model and study the influence factors of its beam transmission, energy conversion, output power, and spectral efficiency. Numerical results shows that the proposed RB system can realize 16 W electric power output with 11 % end-to-end conversion efficiency, and support 18 bit/s/Hz spectral efficiency for communication.

Index Terms—Optical communication; Resonant beam communications; Wireless power transfer; Wireless charging

I. INTRODUCTION

Accompanied by the growth of the Internet of Things (IoT), network capacity continues to increase due to rapidly growing number of devices [1]. At the same time, the energy consumption of mobile devices is also increasing dramatically to support high-performance communication and computation [2]. Facing these challenges, various technologies have been promoted, e.g., wireless power transfer (WPT), ultra-dense cloud radio access networks, etc. [3], [4]. Among them, WPT for providing unlimited energy supply is undoubtedly one of the most attractive solutions [5]. Compared with wired power supply, WPT is flexible and suitable for mobile devices; compared with battery, WPT is not restricted by battery’s capacity, weight, or volume [6], [7].

Based on the WPT, simultaneous wireless information and power transfer (SWIPT) technology has attracted great attention by researchers to address both the energy and data demands at the same time (Fig. 1). SWIPT technologies have many forms with different system structure depending on the carrier. SWIPT system utilizing radio frequency (RF) as carrier is one of typical schemes. It depends on the mature RF communication technology, which has the characteristics of low cost, long transfer distance, and expansive coverage. However, humans may be physical damage in the presence of high density RF radiation. Thus, the researchers must gain more thorough understanding of potential health and safety impacts associated with the usage of SWIPT in public settings [8]. Optical beams such as visible light can also be applied as the SWIPT carrier. The optical SWIPT scheme effectively harnesses the unique properties of light to support high-power energy transfer. This approach also offers significant communication advantages, including access to an extensive license-free spectrum, zero electromagnetic interference, and the capability for high-speed data transmission [9], [10]. However, typical optical beams schemes are limited by alignment, safety, etc.

As one of the optical beams scheme, resonant beam system (RBS) was proposed for self-alignment, and radiation safety light transmission [11], [12]. The transmitter of the RBS is combined with the receiver to form a spatially separated resonator (SSR). The resonant beam generates in the cavity and carrying energy and information transfers between the transmitter and the receiver through the reflectors. Due to the beam concentration characteristics, RBS can support high power transfer [13]. Moreover, by cooperating retro-reflectors, RBS enables self-alignment between the transmitter and the receiver for mobile SWIPT [14]. When the light path between the transmitter and the receiver is blocked thanks to the
separate resonant cavity structure, the cyclic reciprocating process of the resonant beam in the cavity will interrupt immediately, which prevents foreign objects from continuous radiative exposure, ensuring the human safety [15]. Besides, as the aforementioned statement, since the light beam is the signal carrier in the RBS, it can allow high-rate data transfer and developed nan conversion efficiency. Due to these remarkable advantages, the RBS has been applied in various SWIPT applications such as unmanned aerial vehicles (UAV), smartphones, monitors, etc. [17], [18].

The theoretical model, system design, deployment of the RBS have been studied in the literature recently. Firstly, Zhang et al. verified that the RBS can support 2 W WPT with 1% end-to-end conversion efficiency in experiment [13]. Sheng et al. demonstrated an efficient, long-distance scheme using cat-eye reflectors to realize transmitter alignment, a telescope to concentrate beams, and adopting aspheric lenses to fix spherical aberration [19]. In [20], Zhang et al. characterized a long vertical external-cavity surface-emitting lasers resonator scheme for wireless charging. Moreover, to support multi-devices access into the RBS, Xiong et al. proposed a time-division multiple access (TDMA) RBS design for wireless power transfer [21]. Xiong et al. proposed the RBS communication design and the analytical model in [22]. Liu et al. presented the basic SWIPT model of the RBS and demonstrated its mobile ability using the retro-reflectors [14]. To evaluate the safety of the RBS, Fang et al. proposed an analytical model based on electromagnetic field analysis and assessed its safety with external object invasion [15].

Previous research has underscored the features and potential of Resonant Beam (RB) technology in Simultaneous Wireless Information and Power Transfer. Nevertheless, the original RB scheme still has been challenged by significant energy conversion losses, resulting in a merely approximate 1% energy conversion efficiency across short distances [13]. The relatively low conversion efficiency of this technology presents challenges for its application in power supply scenarios for devices under a low-carbon and energy-saving context. Moreover, due to the suboptimal transmission efficiency, the system requires a greater input to satisfy the power demand at the output end. This situation imposes further challenges on system cooling, safety, and component durability.

In this study, we present a novel RB-SWIPT scheme designed to elevate both power transmission efficiency and communication efficacy. We propose the use of a semiconductor gain medium, in contrast to the conventional solid-state medium. Semiconductors exhibit superior energy absorption capacity from the pump source, thus promoting a more effective energy level transition and population inversion efficiency. Consequently, the power threshold decreases, thereby improving the overall conversion efficiency. Additionally, we integrate a telescope internal modulator (TIM) into the resonator. The TIM serves to compress the beam, thereby harmonizing with the smaller dimensions of the gain medium and subsequently reducing transmission loss. This strategic modification underlines our commitment to enhancing the efficiency of SWIPT systems.

The contributions of this paper are summarized as follows:
• A high-efficiency RB-SWIPT scheme is proposed. By adopting the semiconductor gain medium and the telescope internal module, the scheme can achieve long-range, high-rate, and energy conversion efficiency enhanced SWIPT.
• An analytical model of the proposed scheme is developed, which can describe the energy conversion, the beam propagation, the electric power output, and data transfer capability of the system. An evaluation for system performance and a guidance for parameters optimization is provided.

The remainder of this paper is structured as follows: Section II details the high-efficiency RBS system, including descriptions of the semiconductor gain medium and TIM. Section III presents a numerical evaluation of the system’s performance. Concerns related to the beam splitting process are discussed in Section IV. Finally, Section V concludes the paper.

II. SCHEME ANALYSIS AND MODEL ESTABLISHMENT
In this section, we will state the function principle of the scheme on realizing high-efficiency resonant beam charging and communication and develop the analytical model.

A. System Structure and Semiconductor Gain
The system structure of the proposed RB-SWIPT scheme is briefly depicted in Fig. 2. Overall, the system can be divided into three parts: transmitter, receiver, and spatially separated resonator. The transmitter is mainly composed of a gain medium, a pump source and a data loader. The data loader can load the electric signal into the pump source for data transfer. Then, the pump source releases beam carrying the data signal in the form of optical radiation to the gain medium. The gain medium receives the energy and occurs the stimulated absorption, spontaneous emission, and stimulated emission, generating photons to form resonant beams. The receiver mainly includes three elements: photovoltaic (PV) panel module, beam splitter, and avalanche photodiode (APD) module [23], [24]. The beam splitter is applied to accept the external beams output from the M2 and split them into two rays for independent energy harvesting and data receiving. The PV module receives one of the rays for energy harvesting where the optical energy can be converted into electrical power after photovoltaic conversion. The APD module captures the remaining rays for data reception, where the light signal is detected. The spatially separated resonator is made by reflectors M1, M2, and a TIM. Among them, M1 and M2

![Fig. 2. High-efficiency resonant beam SWIPT system](image-url)
constitute the resonant cavity for beams oscillation. The TIM is placed on the optical path in front of the gain, which is used to change the phase of the resonant beam for beam compression and promoting the beam incidence.

The proposed RB scheme applies the semiconductor materials to compose the gain medium for efficiency enhanced. Semiconductor material utilizes the recombination of electrons in the conduction band and holes in the valence band to generate simulated radiation [25], which has the following characteristics: 1) The materials with different ingredients on gain medium developing window layer, active area, and distributed Bragg reflector layer (DBR) have a band-gap difference forming a potential barrier. It will confine electrons and holes within the gain area, which is conducive to the recombination of electrons and holes; 2) The active area and the cladding layers have a refractive index difference. When photons transfer on the material boundary, they will be reflected back to the active area. As a result, the light field can be restricted in the active area, which causes more stimulated radiation generation; 3) The semiconductor gain can be made as a hetero-junction quantum well structure. This structure (Fig. 3) can further reduce the thickness of the active layer to the nano-level producing the quantum effect, which makes the limitation of carriers and light fields be further strengthened, and causes the energy level difference decreasing from $E_g$ to $E_{gw}$ [26], [27]. Thanks to these characteristics, the particle conversion loss in the semiconductor gain is significantly minimized, resulting in a substantial reduction of the threshold value.

**B. Resonant Beam Power and Conversion Efficiency**

In the gain medium of the proposed optical system, photons are generated and subsequently propagate within the cavity. This process results in the formation of a resonant beam. The resonant beam, functioning as a carrier, transmits both energy and signal to the designated receiver.

To assess the transmission efficacy of the system, the beam power output at reflector M2 serves as a crucial figure of merit. Additionally, the system exhibits a characteristic threshold power due to inherent energy losses. The output beam is only generated when the input power surpasses this threshold condition. Furthermore, the relationship between input and output power is governed by a conversion efficiency ratio. This ratio is a function of the energy conversion process occurring at each stage within the system. Based on the cyclic power principle and materials characteristic of the gain medium [28], [29], the external beam power can be defined as:

$$P_{beam} = (P_{in} - P_{th}) \eta_s, \quad (1)$$

where $P_{in}$ denotes the input electric power, $P_{th}$ expresses the threshold power, and $\eta_s$ is the slope efficiency.

Firstly, $\eta_s$ is related to the system structure such as the reflectivity of M1, which can be depicted as:

$$\eta_s = \eta_{p} \eta_{pa} \lambda_{pump} \ln (R_2) \lambda_{beam} \ln (R_1 R_2 V), \quad (2)$$

where $R_1$ and $R_2$ denote the reflectivity of the reflectors M1 and M2, $\eta_{p}$ is the pump conversion efficiency, $\lambda_{beam}$, $\lambda_{pump}$ represent the wavelength of resonant beams and pump beams, $V = V_c V_d$ expresses overall energy losses which mainly includes constant loss $V_c$ (absorption dispersion of reflectors and air, internal loss in the gain) and beam diffraction loss $V_d$.

Secondly, $P_{th}$ is determined by the gain medium, which can be expressed as:

$$P_{th} = A_s h c l N_{th} \frac{\eta_{pa}}{\lambda}, \quad (3)$$

where $A_s$ expresses the effective active cross-section, $h$ denotes the Planck constant, $c$ is the speed of light in vacuum, $\lambda$ represents the beam wavelength, $l$ is the length of the gain medium, $N_{th}$ denotes the threshold carrier density in gain medium, $\eta_{pa}$ expresses the pump absorption efficiency, and $\tau$ is the carrier attenuation time.

Normally, $\tau$ can be expressed as [29]:

$$\tau = (\alpha + \beta N_{th} + \gamma N_{th}^2)^{-1}, \quad (4)$$

where $\alpha$, $\beta$, and $\gamma$ express recombination coefficients of the gain medium. $N_{th}$ is related to the gain factor, which can be described as:

$$N_{th} = N_0 \exp (g/g_0), \quad (5)$$

where $g_0$ is gain coefficient under low pump power, $N_0$ denotes the transparency carrier density, and $g$ expresses the saturation gain coefficient.

To define the parameter $g$, it is essential to analyze the energy saturation condition, characterized by an equilibrium between gain and loss within the system [28]. According to Fig. 2, the spatially separated resonator cavity includes...
refectors M1, M2, TIM, and gain medium. During the propagation of the resonant beam within the cavity, optical elements, notably M1, either absorb or reflect a portion of the beam, resulting in energy losses. Conversely, energy is gained in the gain medium. Consequently, if the beam, after completing one round-trip within the cavity, returns to its point of origin with its energy unaltered, it can be inferred that the system has attained a state of equilibrium between loss and gain. This specific equilibrium state is referred to as the saturation condition. From Fig. 4 after one-trip energy cycle, the initial energy density will become \( IR_2 R_1 G^2 V^2 \) from \( I \). When the saturation condition is satisfied, the \( IR_2 R_1 G^2 V^2 \) should equal to \( I \), and parameters have the relationship as:

\[
R_1 R_2 G^2 V^2 = 1, \tag{6}
\]

where \( G = \exp(\Gamma g l) \) expresses the overall gain factor (each time the beam travels through the gain, the beam energy intensity will increase by \( G \) times), \( R_1 \) and \( R_2 \) can be considered as the beam emission ratio of M1 and M2. At this time, \( g \) can be depicted as:

\[
g = -\frac{\ln(R_1 R_2 V^2)}{2l}. \tag{7}
\]

Further, taking the (7) into (5), the \( N_{th} \) can be denoted as:

\[
N_{th} = N_0(R_1 R_2 V^2)^{-2g_0(\Gamma)^{-1}}, \tag{8}
\]

where \( \Gamma \) is the longitudinal confinement factor.

Finally, based on aforementioned formulas, the \( P_{beam} \) presented in (1) can be depicted. At the end, the beam transmission efficiency can be defined as:

\[
\eta_b = \frac{\eta_p \eta_{po} \lambda_{pump} \ln(R_2)}{\lambda_{beam} \ln(R_1 R_2 V)} \left( 1 - \frac{A_s h c l N_{th}}{\lambda \eta_p \eta_{po} \tau P_{in}} \right). \tag{9}
\]

C. Beam Transmission Description and Diffraction Loss

To analyze the resonator structure, the process of beam transmission in the resonator should be described at first. In this paper, we adopt beam vectors and transmission matrices to define the beam propagation. Specifically, based on the beam physics characteristics (straight line propagating), we can depict it as \( \vec{r} = (x, \theta_x) \), where \( x \) expresses the position parameter on the coordinate axis and \( \theta_x \) represents the propagation direction of the beam. Assuming a beam originates at a specific point and propagates in free space from \( x_1 \) to \( x_2 \), with an initial transmission angle denoted as \( \theta_1 \), the beam’s trajectory can be represented using vector notation. Initially, the beam vector is expressed as \( \vec{r}_1 = (x_1, \theta_1) \). As the beam progresses along its path to a position \( z \), its vector representation evolves to \( \vec{r}_2 = (x_2, \theta_2) \), indicating the change in both position and transmission angle. The process of vectors conversion from \( \vec{r}_1 \) to \( \vec{r}_2 \) can utilize matrix M to express, which is \( \vec{r}_2 = M \vec{r}_1 \). Moreover, when the beam passes through a series of optical components, the entire process can be expressed as the matrices of these components multiplied in the corresponding order.

By employing the aforementioned beam vectors and the transmission matrices, it is possible to define the optical elements and characterize the beam transfer within the cavity.

Firstly, we adopt it to depict the reflectors. The reflectors introduce in the scheme involving in a convex lens (focal length: \( f \)) and a reflective mirror. The reflective mirror is located at the exit pupil of the lens with distance \( d \), and its surface is flat (infinite focal length). Using the typical matrices’ expression of lenses and mirror [28], the reflector can be described as:

\[
M_r = \begin{bmatrix}
1 & f \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
-1/f & 1
\end{bmatrix}
\begin{bmatrix}
d & 0 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
= \frac{\exp(-1/f r)}{1/ f_r -1},
\tag{10}
\]

where

\[
f_r = \frac{f^2}{2(d-f)}.
\tag{11}
\]

Reflectors can reflect incident beams back toward the parallel path of the original one, which is precondition of the self-alignment [14]. To realize ideal retro-reflect in the proposed reflectors, we design \( d = f \), which denotes the mirror is put at the focal point of the lens.

To effectively compress resonant beams, we have introduced the TIM technique and employed matrix representation to characterize and describe the TIM. From Fig. 5 lenses L1, L2 with focal length \( f_1 \), \( f_2 \) compose the TIM, which can be depicted as:

\[
M_{TIM} = M_{L2} M_{L1} M_{t}, \tag{12}
\]

where \( M = f_1/f_2 \).

Building on the previously mentioned matrices and referring to Fig. 5 we can define the one trip beams transmission in the resonator. Taking reflector M1 as the starting point, the beam propagating in the cavity will pass through lens 1, lens 2, and reflector M2 in sequence. This process can be expressed using the following matrix representation:

\[
M_{c} = M_{M2} M_{d3} M_{L2} M_{M1} M_{d2} M_{d1} M_{M1} M_{d1} M_{L1} M_{M2} M_{d2} M_{d3} M_{M1}
\]

\[
= \begin{bmatrix}
-1 & 0 \\
\frac{-1}{f_2} & -1
\end{bmatrix}
\begin{bmatrix}
1 & d_3 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
-1/f_2 & 1
\end{bmatrix}
\begin{bmatrix}
d & 0 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
n & 1 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
-1 & f_{1/r}
\end{bmatrix}
-1, \tag{13}
\]

where \( M_{M1} \), \( M_{M2} \), \( M_{L1} \), and \( M_{L2} \) express the matrix of reflector M1, M2 with effective curvature factors \( \rho_1 \) and \( \rho_2 \), and lenses L1, L2 with focal length \( f_1 \) and \( f_2 \). \( M_{d1} \), \( M_{d2} \), \( M_{d3} \), and \( M_{L1} \) express the beam transfer in the space with distances \( d_1 \), \( d_2 \), \( d_3 \) and \( l_1 \).

To accurately determine the diffraction loss, it is essential to depict the beam’s distribution along the vertical propagation direction. The beam spot effectively characterizes the beam’s vertical distribution, with its radius being a commonly used metric to evaluate the beam’s lateral amplitude at a given
In Section II.A, the external beam carrying point. Given that the intensity cross-section of the beam is circular, we utilize the spot radius as the key parameter for this evaluation. According to [30], [31], the beam spots radius on the reflectors of the resonant cavity can be defined by \( M_c \). Furthermore, given that the gain medium is strategically positioned on the transmitter side, and considering that the distance \( d_1 \) is relatively small, it can be inferred that the spot size on the gain medium is approximately equivalent to the spot size on reflector M1. In this case, the beam spot radius on the gain medium can be given by:

\[
\begin{align*}
M_c & = \begin{bmatrix} A_c & B_c \\ C_c & D_c \end{bmatrix} \\
\omega_g & = \left( \frac{\chi^2 B_c D_c}{\pi^2 A_c C_c} \right)^{1/4},
\end{align*}
\]

where \( A_c, B_c, C_c, \) and \( D_c \) are the matrix elements of \( M_c \) which is depicted in [13]; \( \lambda \) is the wavelength of the resonant beam. Further, the beam diffraction loss \( V_d \) can be defined as [32]:

\[
V_d = 1 - \exp(-2a^2/w_0^2),
\]

where \( a \) denotes the radius of gain medium.

D. Electric Power output and Spectral Efficiency

As outlined in Section II.A, the external beam carrying the signal will emerge from reflector M2 at the receiver’s end. Subsequently, a beam splitter is employed to divide this external beam into two distinct paths. One portion is directed towards the photovoltaic (PV) cell, facilitating electric energy harvesting (EH). The other portion is captured by the Avalanche Photodiode (APD) for the purpose of data reception.

1) Electric power output: Firstly, part of the external beam separated by the beam splitter is transmitted to the surface of the photovoltaic cell through a homogenizing waveguide. Then, the beam will be converted into electrical power output through photoelectric conversion. This process can be briefly expressed by the following formula [33]:

\[
\begin{align*}
P_p & = \mu P_{\text{beam}}, \\
P_{\text{out}} & = \eta_p P_p + P_{\text{th}}.
\end{align*}
\]

where \( \mu \) is the power split ratio, \( P_p \) expresses the beam power received by the PV. The parameter \( \eta_p \) is the slope efficiency of photoelectric conversion, and \( P_{\text{th}} \) is the threshold power of PV. It should be noted that, in order to simplify the simulation process, \( P_{\text{out}} \) is represented using a linear model. This approach is based on the experimental findings presented in [34], and assumes ideal conditions for both heat dissipation and the receiving area of the PV (photovoltaic) system. In practice, the beam energy absorbed by PV is limited, it is expected that the conventional linear EH model is only accurate for the specific scenario when the received powers at the receiver is in a constant power range and the nonlinear EH model has a better applicability [35]. Further, the end-to-end energy conversion efficiency is depicted as:

\[
\eta_E = \frac{\eta_p P_p + P_{\text{th}}}{P_{\text{in}}},
\]

2) Spectral efficiency: The residual portion of the external beam, segregated by the beam splitter, is incident upon the APD. The APD functions to convert this optical signal into an electrical signal, concurrently facilitating data reception. This conversion process can be illustrated as follows:

\[
\begin{align*}
P_D & = (1 - \mu)P_{\text{beam}}, \\
I_{\text{out}} & = \nu P_D,
\end{align*}
\]

where \( \nu \) is the optical-to-electrical conversion responsivity of APD.

Moreover, photoelectric conversion will produce thermal noise and shot noise when APD is receiving data. Among them, thermal noise can be expressed by the following formula [36]:

\[
n_{\text{thermal}}^2 = \frac{4kTB_x}{R_L},
\]

where \( k \) is the Boltzmann constant, \( T \) is the background temperature, and \( R_L \) is the load resistor. In addition, the formula about the shot noise factor is [36]:

\[
n_{\text{shot}}^2 = 2q(I_{\text{out}} + I_{\text{bg}})B_x,
\]

where \( q \) is the electron charge, \( B_x \) is the bandwidth, \( I_{\text{bg}} \) is the background current. At this point, the additive white Gaussian noise (AWGN) of the communication module can be defined:

\[
N_M^2 = n_{\text{shot}}^2 + n_{\text{thermal}}^2.
\]

Finally, we can obtain spectral efficiency of the system as [37]:

\[
\tilde{C} = \frac{1}{2} \log_2 \left( 1 + \frac{P_{\text{out}}^2}{2\pi c N_M^2} \right),
\]

where \( e \) is the natural constant.

III. SIMULATION CALCULATIONS AND RESULTS ANALYSIS

In this section, we will evaluate the performance of the proposed system by analyzing the resonant beam distribution, received beam power, output electric power and channel capacity.
A. Resonant Beam Distribution

In order to match the semiconductor gain, the proposed RB system introduce a built-in TIM, which can modulate the phase of the beam to achieve the beam compression. To evaluate the compression performance, we apply the beam spot radius defined in the previous chapter, analyzing its changes with different structure parameters.

1) Parameter Setting: The gain medium is composed of semiconductor material GaAsP, which can generate light beam with 980 nm wavelength. It is placed obliquely and is 20 mm away from M1. Based on the Section II.C, we take the value of \( f_{r_1} \) as infinite (\( d = f \)). Then, to constrain the beam to maintain par-axial propagation, the \( f_{r_2} \) of M2 is set as variable. The TIM is positioned on the side of the gain medium, and its position parameter is set to \( d_2 = 20 \) mm relative to the gain chip. The focal length of the concave lens of the TIM is designed as \( f_1 = -5 \) mm. We take the end-to-end distances \( d_3 \) from 2 m to 10 m, and TIM structure parameter \( M \) as the inspection point, respectively. Finally, considering the beam spot radius will be different at different distances, we take the maximum value of the spot radius \( \omega_{g, \text{Max}} \) on the gain medium to evaluate.

2) Calculation results and analysis: Fig. 6(a) presents the calculation results which depicts the relationship of the TIM structure parameter \( M \) and the maximum beam spot radius \( \omega_{g, \text{Max}} \). As can be seen, when the value of \( M \) increases, the \( \omega_{g, \text{Max}} \) shows a downward trend. When \( M \) is in the range of 2 to 6, the beam radius decreases rapidly. Then, when \( M \) is greater than 10, the decline of the beam spot tends to be gentle, which indicates that compression capacity is limited. Moreover, if the \( M \) is beyond the range, the compression tends to be stable, and if \( d_3 \) takes a large value, the overall \( \omega_{g, \text{Max}} \) will increase. In numerical, the incident beam can be compressed from 1.2 mm to around 0.1 mm, which is only 1/12 of the original beam. Fig. 6(b) depicts curves of \( \omega_{g, \text{Max}} \) as a function of \( d_3 \). As it presented, in the original scheme without TIM (where \( M = 1 \)), the radius of beam presents a great trend of increase when \( d_3 \) enhances. In contrast, the proposed scheme with TIM shows a gentle trend of increase. Numerically, the value of \( \omega_{g, \text{Max}} \) in proposed scheme is below 0.25 mm while the original scheme is greater than 0.5 mm. Further, we analyze the influence of \( f_{r_2} \) parameter on beam compression. Fig. 6(b) describes curves of maximum beam radius on the gain versus \( f_{r_2} \) parameters of reflector M2. As depicted, \( \omega_{g, \text{Max}} \) exhibits an upward trend as the value of \( f_{r_2} \) increases. Subsequently, the curves demonstrate a downward shift with the increase in the value of \( M \). Overall, the increase in \( f_{r_2} \) tends to have a detrimental effect on beam compression, as evidenced by the enlargement of the beam spot.

B. Received Beam Power

According to Section II.A, after the energy accumulating, the external beam will eventually emerge from reflector M2. Then, it will enter the PV and APD respectively under the function of the beam splitter, realizing the electric power output and data reception. Usually, we can adopt the received beam power \( P_{\text{beam}} \) to evaluate the end-to-end beam transmission performance.

1) Parameter Setting: The gain medium is made of GaAsP. According to the material properties, we set the characteristic parameters such as light quantum, gain factor, etc. and list them in Table II. Furthermore, we adopt a typical laser diode as the pump source whose electro-optical conversion efficiency \( \eta_{pc} \) and absorption efficiency \( \eta_{pa} \) are 0.6 and 0.85. In addition, the effective active cross-section \( A_s \) of the gain is set as \( 3 \times 10^{-4} \) cm\(^2\), the constant loss \( V_c \) takes 0.99, the geometric radius of gain medium \( a \) is 0.5 mm, the pump beam wavelength is 808 nm, the reflectivity of the mirror in M1 is 0.999, and the end-to-end transmission distance is 10 m.
increasing the thickness, we can enhance the performance of beam transmission. From the blue lines in the graph, it is evident that as the reflectivity of mirror M2 (R2) changes from 0.8 to 1, both the received beam power and the beam conversion efficiency initially increase and then decrease. Moreover, as the input power is increased, the curves representing the beam power (Pbeam) and the beam conversion efficiency (ηb) shift to the left and ascend. Numerically, the maximum value of Pbeam and ηb are obtained when the R2 locates at the range from 0.9 to 0.95.

In Fig. 10 we analyze Pbeam and ηb as the function of the input power P_in. According to the blue lines, the Pbeam will increase as P_in increase, which presents a positive linear relationship with P_in. Moreover, the slope and intercept of lines are affected by R2. A large value of R2 is benefit for reducing the threshold power (line intercept). Besides, from the red curves, the ηb will be also enhanced by P_in increase. However, different from Pbeam, curves are nonlinear and gradually flattens out. Further, we evaluate the performance of received beam power Pbeam as the function of transmission distance d3, which is shown in Fig. 11. As can be seen, curves of Pbeam present a downtrend with the increase of the d3 which proves the negative impact of the transmission loss on beam output (Section II.C). What’s more, with the value of M increases, curves become flattened. It indicted that the transmission loss can be restrained by TIM. In numerical, the value of Pbeam can maintain 40W output over 15m distance.

C. Output Electric Power and Channel Capacity

To evaluate the received beam power, we have examined the factors influencing both Pbeam and ηb. Additionally, it is necessary to analyze the performance of the PV cell and the
APD in the context of simultaneous wireless information and power transfer (SWIPT).

1) Parameter Setting: To evaluate the SWIPT performance, the PV and APD structure parameters should be defined. According to [34], PV cell structure parameters $\eta_p$ and $P_{\text{pth}}$ are set as 0.3487 and -1.535 W, respectively. In the proposed system, the environment temperature is taken as $T=300$ K, the electronic charge $q$ is $1.6 \times 10^{-19}$ C, and the Boltzmann constant $k$ is $1.38 \times 10^{-23}$ J/K. The APD for light signal receiving is commercial sensors for 980 nm wavelength. Then, based on [36], [38]–[40], we set the conversion responsivity of the APD $\nu=0.6$ A/W, the noise bandwidth $B=811.7$ MHz, the background current $I_{\text{bg}}=5100$ $\mu$A, and the load resistance $R_L=10$ KΩ.

2) Calculation results and analysis: Fig 12 depicts the curves of spectral efficiency, output electric power, and end-to-end conversion efficiency versus beam splitting ratio. Observing the blue line, the entire curve exhibits a downward trend as $\mu$ increases. Initially, this decline is relatively gradual. However, when $\mu$ exceeds 0.8, $C$ starts to decrease sharply. From the red and green lines with markers, it is evident that both $P_{\text{Eout}}$ and $\eta_E$ exhibit a positive linear relationship with $\mu$. Their values increase as $\mu$ increases. Numerically, the spectral efficiency $C$ can reach 17.69 bit/s/Hz when $\mu$ is set to 0.99, at which point $P_{\text{Eout}}$ and $\eta_E$ are also high. Therefore, this value of $\mu$ can be chosen as the beam splitting ratio to achieve high-efficiency SWIPT.

Besides, we also explore the relationship of spectral efficiency, output electric power, and end-to-end conversion efficiency versus input power, which is presented in Fig. 13. From the blue line, it’s apparent that the spectral efficiency rapidly ascends to a larger value. In general, the greater the input beam energy, the higher the spectral efficiency the scheme achieves. However, this effect is somewhat limited. As the input power continues to increase, the system’s spectral efficiency tends to stabilize. For instance, when $P_{\text{in}}$ is increased from 50W to 150W, the spectral efficiency experiences only a modest increase of 1 bit/s/Hz. Furthermore, as indicated by the red and green lines, both $P_{\text{Eout}}$ and $\eta_E$ exhibit a positive relationship with $P_{\text{in}}$, where $P_{\text{Eout}}$ shows a linear trend and $\eta_E$ demonstrates a nonlinear one. In numerical, $P_{\text{Eout}}$ and $\eta_E$ can reach up to 16 W and 0.11, respectively, at $P_{\text{in}}=150$ W.

Generally, by optimally matching the splitting ratio with the input power, the system’s data transmission spectral efficiency can achieve 16-18 bit/s/Hz, supporting 0-16 W of electric power. This demonstrates the system’s potential for high-rate and high-power SWIPT.

D. Summary

In summary, after numerical evaluation and analysis, we conclude that the proposed RB SWIPT scheme is capable of providing 16 W electrical energy harvesting and 18 bit/s/Hz spectral efficiency for communication, with 11% energy conversion efficiency and 10 m transmission distance. Table II presents the performance comparison between our system and the existing architectures, clearly demonstrating the advantages
of the proposed RB SWIPT in delivering high power, maintaining high spectrum efficiency, and ensuring high energy conversion efficiency over long transmission distances.

IV. DISCUSSION

A. Transmission Model by Electromagnetic Field Propagation

In the aforementioned sections, we have developed end-to-end beam transmission model based on linear optics using beam matrices. Additionally, considering the electromagnetic field characteristics of light waves, we can also adopt electromagnetic field propagation to conduct exact analyses for the amplitude and phase distribution of the light field. The theoretical framework for describing electromagnetic field propagation is derived from Maxwell’s equations, leading to the wave equations for electric and magnetic fields, as cited in [45]. Furthermore, according to Huygens-Fresnel principle, during the propagation of light, the field distribution at any point is determined by the coherent superposition of the wavelets of the incident wave at that point [46]. By understanding the field distribution of the initial point light wave, denoted as \( u(x, y) \), we can apply diffraction theory to express its field distribution at a specific point ‘s’ on the transmission path as \( u'(x, y) \). This approach allows us to accurately represent the beam transmission within the resonator. Building on this, we can incorporate the boundary conditions of the resonator in our proposed system to describe the changes in the light field of the beam over a complete end-to-end cycle. Furthermore, by considering the beam generation from the self-reproductive mode, as mentioned in [47], as a criterion for stable output, we can determine the steady-state light field distribution.

Fig. 14 presents the field distribution on the gain medium: (a) without TIM; (b) with TIM

### TABLE II

| Technology      | Ref. | Conversion Efficiency | Spectral Efficiency | Output Power | Transmission Distance |
|-----------------|------|-----------------------|---------------------|--------------|-----------------------|
| Visible light   | [41] | \(3.0 \times 10^{-3}\) % | 6 bit/s/Hz          | 2.96 mW      | 1.5 m                 |
| Radio frequency | [42] | 8.44 \times 10^{-7} %  | 8 bit/s/Hz          | 0.38 mW      | 3.0 m                 |
| Resonant beam   | [43] | 1.375 \times 10^{-4} % | Not stated          | 5.5 \(\mu\)W | 10 m                  |

This work          | 1\%   | 18 bit/s/Hz           | 16W                | 15 m         |

be seen, the incident beam on the gain medium has been effectively compressed in the proposed system with TIM. In contrast, beam has a large field distribution with low beam quality (uneven distribution) in the original system without TIM. This analysis corresponds to the results obtained using the matrix model in Section V, further verifying the feasibility of our proposed scheme. Overall, electromagnetic field propagation analysis is beneficial for evaluating the beam’s quality, system structure, etc. However, it’s important to note that as fast Fourier transform and the Fox-Li iterative method are employed in these calculations, they demand significantly more computing power and time compared to the transmission matrix method introduced in the second section of this paper. Future research will delve deeper into the benefits and results of this method.

B. System Experiment and Applications

In this paper, we propose a high-efficiency RB charging and communication scheme, provide an analytical model, and evaluate system performance through simulation. For practical implementation of the RB-SWIPT scheme in IoT applications, we should discuss the system deployment and applications in IoT.

1) System deployment: As illustrated in Fig.2 and Fig.5, the system incorporates several lenses. These lenses can be made of N-BK7 glass, known for its high laser damage threshold, and are coated with an anti-reflective layer to reduce beam loss. Reflectors M1 and M2 are designed with a cat-eye structure, as detailed in Section II.C. This design includes a convex lens and a flat mirror aligned in parallel, with their optical centers overlapping to create a focus-free system. Additionally, reflectors utilizing a corner-cube structure, as shown in Fig. 15(a), are also suitable for this system to facilitate beam retro-reflection. Furthermore, to realize beam separated, optical splitters are introduced in the receiver. Normally, beam splitters such as cube beam-splitters can be used to separate the external beam, which are demonstrated in Fig. 15(b). Cube beam-splitter consists of two classical right angle prisms which can also consist by N-BK7 glasses. The hypotenuse surface of one prism has a coating for beam splitting, and the two prisms are cemented together, forming a cubic shape. When beams incident, part of the beam will transmit through it, and the other part of the beam is reflected by the coating and propagates in the vertical incident direction.

The gain module utilized in our system is an open-cavity surface-emitting semiconductor gain, requiring specific customization. As depicted in Fig. 3, the semiconductor gain
ensuring reliable data transmission. We introduce a composite beam technology not only facilitates reliable data transmission as a ‘thing’ node in the IoT network. The use of resonant data from sensors, adjusting its flight path, or functioning module is composed of several material regions. Central to these is the Distributed Bragg Reflector (DBR) layer and the gain layer, both of which are fabricated using material growth equipment. This fabrication process involves creating a multilayer stack structure with alternating high and low refractive indices, along with the quantum well structure previously mentioned. The topmost layer of the module serves as the photon exit for light emission, which can be optimized with an anti-reflection coating to minimize optical losses. The bottom layer functions as a thermal dissipation layer, typically made from a high thermal conductivity metal that is compatible with the semiconductor materials used. Drawing on the analysis of the critical experimental factors previously discussed, and through the rational arrangement of components, we can effectively construct the experimental platform.

2) System applications: To demonstrate the practical applications of our system, consider its use in real-time Internet of Things (IoT) scenarios, such as with unmanned aerial vehicles (UAVs). UAVs, known for their exceptional mobility, are excellent candidates for acting as aerial nodes. This role not only extends network coverage but also enhances the flexibility of IoT topology. However, employing UAVs in this capacity requires the system to have robust endurance and superior communication capabilities. The RB-SWIPT system is ideally suited for this purpose, as it can effectively power UAVs while ensuring reliable data transmission. We introduce a composite UAV system design, comprising a short-endurance UAV, an RB-SWIPT station, and a set of buoy sensors. The UAV’s fuselage is equipped with the RB-SWIPT station’s receiver module, enabling wireless charging through resonant beam. This feature is crucial when the UAV is tasked with collecting data from sensors, adjusting its flight path, or functioning as a ‘thing’ node in the IoT network. The use of resonant beam technology not only facilitates reliable data transmission but also helps maintain a higher state of charge for the UAVs. However, the original resonant optical system faced limitations in transmission distance and conversion efficiency due to energy losses, with a maximum transmission distance of only 2.6 meters and a mere 1% conversion efficiency, as reported in [13]. These limitations hindered its application in UAVs. Thus, the innovative approach presented in this paper, which integrates a TIM structure and high-efficiency semiconductor gain modules, significantly enhances both the transmission distance and conversion efficiency. This improvement makes the application of the resonant beam system in UAVs feasible. Furthermore, we have developed a viable communication pathway that facilitates simultaneous energy transmission and information delivery. The establishment of a reliable optical communication channel addresses bandwidth and interference challenges, effectively integrating UAVs as functional nodes in IoT applications. Beyond the UAV application mentioned above, the RB-SWIPT system is versatile enough to be integrated with a wide range of real-time IoT terminals. Examples include human body sensors, cameras, smart doorbells, and other IoT devices. The implementation of this system can effectively address common challenges such as the need for extensive device wiring, excessive battery usage, and radio signal interference. This is achieved by enabling real-time energy and signal transmission, thereby enhancing the efficiency and reliability of IoT networks.

V. CONCLUSIONS

In this paper, we have introduced a high-efficiency resonant beam charging and communication system, which utilizes a semiconductor gain medium and a telescope internal modulator. Grounded in the theories of beam transmission, power conversion, energy harvesting, and data reception, we developed comprehensive analytical models. These models address the beam propagation, beam power, electric power output, and spectral efficiency of our proposed system. Numerical analyses demonstrate that our system exhibits exceptional Simultaneous Wireless Information and Power Transfer (SWIPT) performance. It is capable of producing 16 W of electric power output with an 11% end-to-end conversion efficiency and supporting a spectral efficiency of 18 bit/s/Hz for communication purposes.

There are compelling topics that warrant further investigation in future studies. 1) With respect to the performance of the proposed scheme during actual deployment, its influencing factors, and the discrepancies with the simulation results, the experimental analysis of the system can be conducted in the future. 2) The integration of the proposed system scheme into existing IoT devices, such as system integration, energy reception circuit design, and communication module design, should be thoroughly researched in the future.

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