

Article

Analysis and Design of High-Efficiency Resonant Beam Charging and Communication

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Abstract

With the development of the 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 delivery concurrently. In this paper, we analyze and design a high-efficiency resonant beam (RB) charging and communication scheme. The scheme is based on semiconductor materials for the gain medium, which provide a better energy absorption capacity compared with the traditional solid-state one. Moreover, the telescope internal modulator (TIM), which can concentrate beams to match the gain size, is adopted in the scheme, reducing the transmission loss. To evaluate the scheme’s 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 show that the proposed RB system can realize 16 W electric power output with 11 % end-to-end conversion efficiency, and it can support 18 bit/s/Hz spectral efficiency for communication.

Keywords: optical communication; resonant beam communications; wireless power transfer; wireless charging

1. Introduction

Accompanied by the growth of the Internet of Things (IoT), network capacity continues to increase due to a rapidly growing number of mobile devices [1]. Simultaneously, the energy consumption of mobile devices is also increasing dramatically to support high-performance communication and computation [2]. Facing these challenges, various technologies are being explored, e.g., wireless power transfer (WPT), ultra-dense cloud radio access networks, among others [3,4]. Among these, WPT, offering 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. Furthermore, compared with batteries, WPT is not restricted by capacity, weight, or volume limitations [6,7].

Based on WPT, simultaneous wireless information and power transfer (SWIPT) technology has attracted great attention from researchers to address both energy and data demands (Figure 1). Notably, prior research includes the work by Sangmahamad et al. [8],



Received: 27 May 2026

Revised: 2 July 2026

Accepted: 3 July 2026

Published: 9 July 2026

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who developed an optimization strategy for increasing secrecy rates in multi-user orthogonal frequency-division multiple access (OFDMA) networks by adjusting power splitting ratios and subcarrier allocation. This strategy is crucial for securing energy-harvesting IoT devices. Lu et al. [9] also improved transmission rates in multi-relay IoT systems using SWIPT, proposing an algorithm that efficiently maximizes transmission rates without requiring extra energy sources for relays. Collectively, these studies demonstrate SWIPT's capability to enhance IoT device functionality and network efficiency.

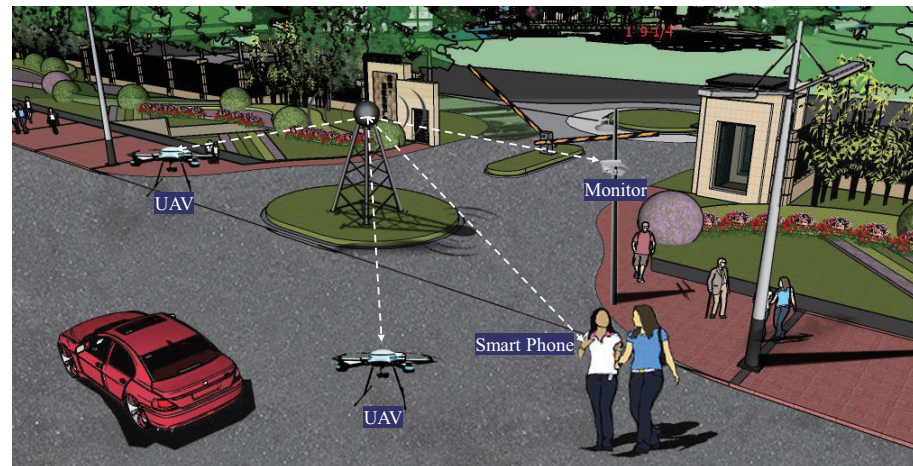


Figure 1. Application scenarios of SWIPT (UAV: unmanned aerial vehicle).

Different SWIPT technologies have different carriers. Radio frequency (RF)-based SWIPT is a typical approach. It leverages mature RF communication technology, known for its low cost, long transfer distance, and expansive coverage. Nevertheless, high-density RF radiation poses a risk of physical damage to humans, necessitating a more thorough understanding of potential health and safety impacts associated with its use in public settings [10]. Alternatively, optical beams, such as visible light, can serve as the carrier. Optical SWIPT effectively leverages aspects like beam divergence control, to achieve high energy conversion efficiency and enable high-power energy transfer. This method also provides advantages for communication, including access to a vast license-free spectrum, immunity to electromagnetic interference, and high-speed data transmission capabilities [11,12]. Conversely, typical optical beam schemes face challenges in alignment, tracking, and safety.

Among optical beam schemes, the resonant beam system (RBS) has been proposed for applications requiring self-alignment and radiation-safe light transmission [13,14]. The RBS comprises a transmitter and a receiver that jointly form a spatially separated resonator (SSR). This SSR generates a resonant beam that carries both energy and information. The system supports high-power transfer due to its beam concentration characteristics [15]. Furthermore, RBS achieves self-alignment between the transmitter and receiver for mobile SWIPT by incorporating retro-reflectors [16]. A key safety feature of RBS is that blocking the light path between the transmitter and receiver immediately interrupts the resonant beam's cyclic process within the cavity, owing to the separate resonant cavity structure. This interruption prevents continuous radiative exposure of foreign objects, thereby ensuring human safety [17]. Furthermore, the use of a light beam as the signal carrier in the RBS enables high-rate data transfer [18]. These remarkable advantages have led to the investigation of RBS in various SWIPT applications, including unmanned aerial vehicles (UAVs), smartphones, and monitors [19–21].

The recent literature has investigated the theoretical model, system design, and deployment of the RBS. For example, Zhang et al. [15] experimentally verified that RBS can support 2 W WPT with 1 % end-to-end conversion efficiency in experiment. Sheng et al. [22]

demonstrated an efficient, long-distance scheme employing cat's eye reflectors for self-alignment, a telescope for beam concentration, and aspheric lenses to correct spherical aberration. Research has also characterized specific RBS schemes, such as the long vertical external-cavity surface-emitting laser resonator scheme for wireless charging presented in [23] by Zhang et al. Regarding system access, Xiong et al. proposed a time-division multiple access (TDMA) design for RBS-based WPT systems [24], and they also contributed the design and analytical model for RBS-based communication systems [25]. Furthermore, Liu et al. [16] presented the basic SWIPT model of the RBS and demonstrated its mobility. Fang et al. [17] proposed an analytical model based on electromagnetic field analysis and assessed RBS safety under external object invasion. In addition to transmission distance and efficiency, the field of view is also important for resonant beam systems [26].

Previous research has underscored the features and potential of RBS technology in SWIPT. Nevertheless, the original scheme still faces challenges from significant energy conversion losses, resulting in a merely 1% energy conversion efficiency across short distances [15]. The relatively low conversion efficiency from the optical-pumped solid-state gain medium observed in present studies presents challenges for power supply scenarios in contexts prioritizing low carbon emissions and energy saving. Moreover, due to this low efficiency, the system requires a greater input to satisfy the power demand at the output end, posing further challenges for system cooling, safety, and component durability.

In this study, we propose a semiconductor-based RB-SWIPT system to increase end-to-end power efficiency. Different from prior RB/RBS wireless power transfer schemes that mainly rely on solid-state gain media, the proposed scheme adopts a GaAsP-based semiconductor gain medium with a quantum-well active region and DBR structure. The semiconductor gain medium exhibits stronger pump absorption and a lower threshold condition, thereby improving the gain and pump-to-beam conversion process. In addition, a telescope internal modulator (TIM) is integrated into the resonator. The TIM is a passive telescope-based intracavity beam-shaping structure. It modulates the transverse phase and beam size of the resonant beam, thereby compressing the beam spot to match the smaller dimensions of the gain medium and reducing transmission loss. Therefore, the efficiency improvement of the proposed RB-SWIPT system is attributed to the combination of the semiconductor gain medium, TIM-assisted beam compression, and output-coupling optimization.

The contributions of this paper are summarized as follows:

- A semiconductor-based RB-SWIPT scheme is proposed. By adopting the semiconductor gain medium and the telescope internal modulator, the scheme can achieve enhanced transmission range, data rate, and energy conversion efficiency in SWIPT.
- An analytical model of the proposed scheme is developed, which can describe the energy conversion, beam propagation, electric power output, and communication capability of the system. An evaluation of system performance and guidance on parameter optimization are also provided.

The remainder of this paper is structured as follows. Section 2 details the semiconductor-based RBS model, including descriptions of the semiconductor gain medium and TIM. Section 3 presents a numerical evaluation for the system performance. Concerns related to the beam splitting are discussed in Section 4. Finally, we conclude in Section 5.

2. System Design and Model Establishment

In this section, we describe the system structure, explain the principle by which the scheme achieves high-efficiency resonant beam charging and communication, and develop the analytical model for performance evaluation.

2.1. RB-SWIPT System with Semiconductor Gain

The system structure of the proposed RB-SWIPT scheme is briefly depicted in Figure 2. Overall, the system can be divided into three parts: the transmitter, the receiver, and the resonant path. 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 a beam carrying the data signal in the form of optical radiation to the gain medium. The gain medium receives the energy and undergoes stimulated absorption, spontaneous emission, and stimulated emission, generating photons to form resonant beams. The receiver mainly includes three elements: a photovoltaic (PV) panel module, a beam splitter, and an avalanche photodiode (APD) module [27,28]. The beam splitter accepts the external beam output from M2 and splits them into two rays for independent energy harvesting and data receiving. The PV module receives one of the rays for energy harvesting, converting the optical energy into electrical power. The APD module captures the remaining rays for data reception, detecting the light signal. The spatially separated resonator is formed by reflectors M1 and M2 and a TIM. Among them, M1 and M2 constitute the resonant cavity for beam oscillation. The TIM is placed on the optical path in front of the gain medium. In this work, TIM denotes a passive telescope-based intracavity optical structure. It changes the phase front of the resonant beam and compresses the beam spot so that the beam can better match the small aperture of the semiconductor gain medium. Under the existing process conditions, through reasonable component layout and circuit design, the receiver of the RB-SWIPT system can be integrated into a variety of IoT sensors or devices to support their demand for power and communication. An illustrative application of this integration is on an unmanned aerial vehicle (UAV), achieving energy supply and information transmission, as depicted in Figure 2.

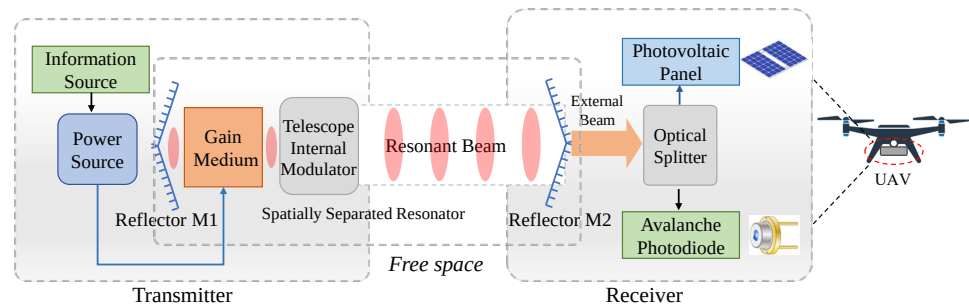


Figure 2. High-efficiency resonant beam SWIPT system diagram.

The RB scheme presented in this paper applies GaAsP-based semiconductor materials to compose the gain medium for enhanced efficiency. Semiconductor material utilizes the recombination of electrons in the conduction band and holes in the valence band to generate stimulated radiation [29], which has the following characteristics: (1) The materials used in the window layer, active region, and distributed Bragg reflector (DBR) layers of the gain medium have different band gaps, forming potential barriers. 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 reach the material boundary, they are reflected back to the active region. 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 (Figure 3) can further reduce the thickness of the active layer to the nanoscale and produce quantum effects, which further strengthen the confinement of carriers and optical fields and decrease the energy-level difference from E_g to E_{gw} [30,31]. Therefore, compared with the solid-state gain medium used in the original RB system, the

semiconductor gain medium mainly contributes to efficiency improvement by increasing pump absorption and reducing the threshold power.

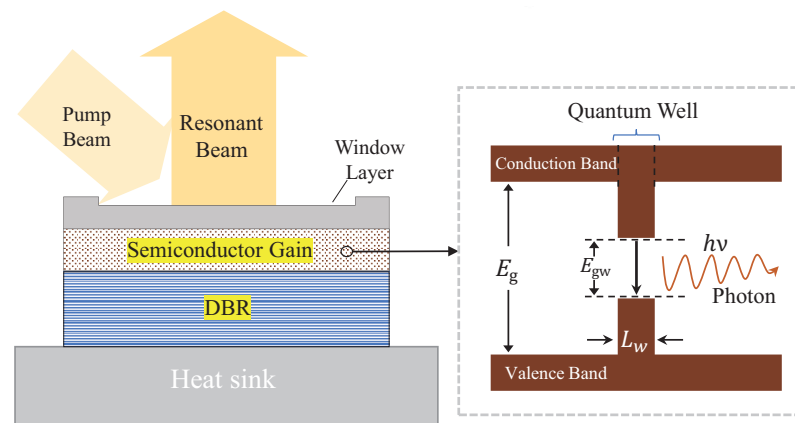


Figure 3. Transmitter structure and operating principles of the semiconductor gain (DBR: distributed Bragg reflector; E_g , E_{gw} : energy level difference; L_w : quantum well length; $h\nu$: photon energy).

2.2. 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 is used as a carrier for transmitting 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 the 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 characteristics of the gain medium [32,33], the external beam power can be defined as follows:

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

where P_{in} denotes the input electric power, P_{th} denotes the threshold power, and η_s is the slope efficiency.

The slope efficiency η_s is related to the system structure such as the reflectivity of M1, which can be depicted as follows:

$$\eta_s = \frac{\eta_{\text{pc}}\eta_{\text{pa}}\lambda_{\text{pump}}[-\ln(R_2)]}{\lambda_{\text{beam}}[-\ln(R_1R_2V)]}, \quad (2)$$

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

The threshold power P_{th} is determined by the gain medium, which can be expressed as follows:

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

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

Specifically, the carrier attenuation of the gain medium τ can be expressed as follows [33]:

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

where α , β , and γ express the recombination coefficients of the gain medium. N_{th} is related to the gain factor, which can be described as follows:

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

where g_0 is the 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 [32]. According to Figure 2, the spatially separated resonator cavity includes reflectors M1 and 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 Figure 4, after one round-trip energy cycle, the initial energy density will become $IR_2R_1G^2V^2$ from I . When the saturation condition is satisfied, the $IR_2R_1G^2V^2$ should equal to I , and the relationship of the parameters is as follows:

$$R_1R_2G^2V^2 = 1, \quad (6)$$

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 denote the reflectivities of M1 and M2, respectively. At this time, g is depicted as follows:

$$g = -\frac{\ln(R_1R_2V^2)}{2l}. \quad (7)$$

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

$$N_{th} = N_0(R_1R_2V^2)^{-(2g_0l\Gamma)^{-1}}, \quad (8)$$

where Γ is the longitudinal confinement factor.

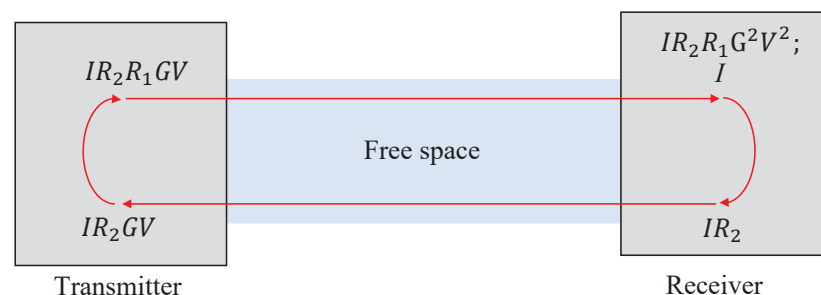


Figure 4. End-to-end energy cycle (I : initial energy density; R_1, R_2 : reflectivity of M1 and M2; G : gain factor; V : path loss).

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

$$\eta_b = \frac{\eta_{\text{pc}}\eta_{\text{pa}}\lambda_{\text{pump}}\ln(R_2)}{\lambda_{\text{beam}}\ln(R_1R_2V)}\left(1 - \frac{A_s h c l N_{\text{th}}}{\lambda\eta_{\text{pc}}\eta_{\text{pa}}\tau P_{\text{in}}}\right). \quad (9)$$

2.3. Beam Transmission Description and Diffraction Loss

To analyze the resonator structure, the beam transmission process in the resonator should first be described. In this paper, we adopt beam vectors and transmission matrices to define the beam propagation. Specifically, based on the rectilinear propagation characteristics of the beam, we can describe it as $\vec{r} = (x, \theta_x)$, where x expresses the position parameter on the coordinate axis and θ_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 θ_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 conversion from $\vec{r}_1$ to $\vec{r}_2$ can be expressed using the matrix $\mathbf{M}$, which is $\vec{r}_2 = \mathbf{M}\vec{r}_1$. 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. First, we adopt it to depict the reflectors. The reflectors we introduce in the scheme involve 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 matrix expression of lenses and mirrors [32], the reflector can be described as follows [34]:

$$\begin{aligned} \mathbf{M}_r &= \begin{bmatrix} 1 & f \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &\quad \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \begin{bmatrix} 1 & f \\ 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} -1 & 0 \\ 1/f_r & -1 \end{bmatrix}, \end{aligned} \quad (10)$$

where

$$f_r = \frac{f^2}{2(d-f)}. \quad (11)$$

Reflectors can reflect incident beams back toward the parallel path of the original one, which is a precondition of the self-alignment [16]. 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. As shown in Figure 5, lenses L1 and L2 with focal length f_1 and f_2 compose the TIM. The TIM consists of a convex lens and a concave lens with collinear optical centers. The focal point of the convex lens in the direction of the concave lens coincides with the negative focal point of the concave lens.

This configuration compresses the beam spot while allowing the output beam to remain collimated. The TIM can be expressed as follows:

$$\begin{aligned} \mathbf{M}_{\text{TIM}} &= \mathbf{M}_{L_2} \mathbf{M}_I \mathbf{M}_{L_1} \\ &= \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & l_t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{bmatrix} \\ &= \begin{bmatrix} \frac{1}{M} & l_t \\ 0 & M \end{bmatrix}, \end{aligned} \quad (12)$$

where $M = -f_1/f_2$.

Building on the previously mentioned matrices and referring to Figure 5, we can define the single-pass beam 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:

$$\begin{aligned} \mathbf{M}_c &= \mathbf{M}_{M2} \mathbf{M}_{d_3} \mathbf{M}_{L2} \mathbf{M}_I \mathbf{M}_{L1} \mathbf{M}_{d_2} \mathbf{M}_{d_1} \mathbf{M}_{M1} \\ &= \begin{bmatrix} -1 & 0 \\ \frac{1}{f_{r2}} & -1 \end{bmatrix} \begin{bmatrix} 1 & d_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & l_t \\ 0 & 1 \end{bmatrix} \\ &\quad \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 \\ \frac{1}{f_{r1}} & -1 \end{bmatrix}, \end{aligned} \quad (13)$$

where $\mathbf{M}_{M1}$, $\mathbf{M}_{M2}$, $\mathbf{M}_{L1}$, and $\mathbf{M}_{L2}$ express the matrix of reflectors M1 and M2 with effective curvature factors ρ_1 and f_{r2} and lenses L1 and L2 with focal length f_1 and f_2 . $\mathbf{M}_{d_1}$, $\mathbf{M}_{d_2}$, $\mathbf{M}_{d_3}$, and $\mathbf{M}_I$ express the beam transfer in the space with distances d_1 , d_2 , d_3 , and l_t .

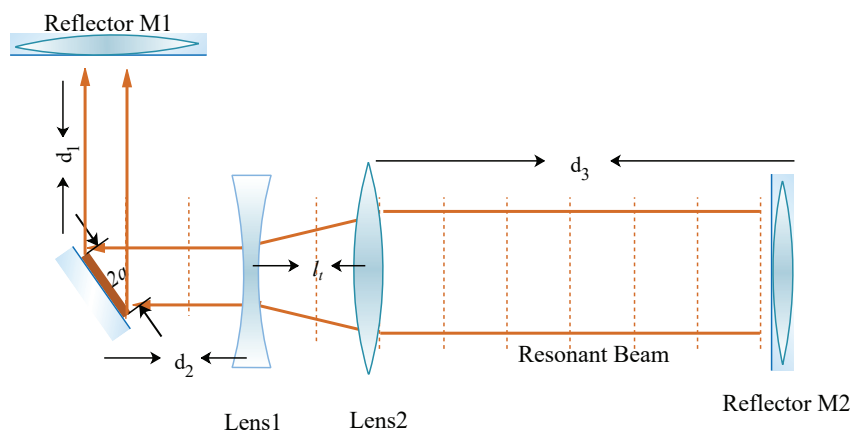


Figure 5. Resonator structure (d_1, d_2, d_3, l_t : element distance; a : radius of gain medium).

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 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 [35,36], the beam spot radius on the reflectors of the resonant cavity can be defined by $\mathbf{M}_c$. 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 the following:

$$\begin{cases} \mathbf{M}_c = \begin{bmatrix} A_c & B_c \\ C_c & D_c \end{bmatrix} \\ \omega_g = \left(-\frac{\lambda^2 B_c D_c}{\pi^2 A_c C_c} \right)^{1/4} \end{cases} \quad (14)$$

where A_c , B_c , C_c , and D_c are the matrix elements of $\mathbf{M}_c$, which is depicted in (13); λ is the wavelength of the resonant beam. Further, the beam diffraction loss V_d can be defined as follows [37]:

$$V_d = 1 - \exp(-2a^2/w_g^2), \quad (15)$$

where a denotes the radius of gain medium.

2.4. Electric Power Output and Spectral Efficiency

As outlined in Section 2.1 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 [38]:

$$\begin{cases} P_p = \mu P_{\text{beam}}, \\ P_{\text{Eout}} = \eta_p P_p + P_{\text{pth}}, \end{cases} \quad (16)$$

where μ is the power split ratio, and P_p expresses the beam power received by the PV. The parameter η_p is the slope efficiency of photoelectric conversion, and P_{pth} is the threshold power of the PV. It should be noted that, in order to simplify the simulation process, P_{Eout} is represented using a linear model. This approach is based on the experimental findings presented in [39], and it assumes ideal conditions for both heat dissipation and the receiving area of the PV 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 [40]. Further, the end-to-end energy conversion efficiency is depicted as follows:

$$\eta_E = \frac{\eta_p P_p + P_{\text{pth}}}{P_{\text{in}}}. \quad (17)$$

(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:

$$\begin{cases} P_D = (1 - \mu) P_{\text{beam}}, \\ I_{\text{Dout}} = \nu P_D, \end{cases} \quad (18)$$

where $I_{D_{out}}$ is the photon current generated by the APD, ν is the optical-to-electrical conversion responsivity of the APD.

Moreover, photoelectric conversion will produce thermal noise and shot noise when APD is receiving light. Among them, the thermal noise can be expressed by the following formula [41]:

$$n_{thermal}^2 = \frac{4kTB_x}{R_L}, \quad (19)$$

where k is the Boltzmann constant, B_x is the bandwidth, T is the temperature, and R_L is the load resistor. In addition, the formula about the shot noise factor is [41]

$$n_{shot}^2 = 2q(I_{D_{out}} + I_{bg})B_x, \quad (20)$$

where q is the electron charge, and I_{bg} is the background light induced photon current. At this point, the additive white Gaussian noise (AWGN) of the communication module can be defined:

$$N_M^2 = n_{shot}^2 + n_{thermal}^2. \quad (21)$$

Finally, we can obtain the spectral efficiency of the communication link as follows [42]:

$$\tilde{C} = \frac{1}{2} \log_2 \left(1 + \frac{I_{D_{out}}^2}{2\pi e N_M^2} \right), \quad (22)$$

where e is the natural constant.

3. Numerical Results

In this section, we evaluate the system performance by analyzing the resonant beam distribution, received beam power, output electric power, and channel capacity.

3.1. Resonant Beam Distribution

In order to match the semiconductor gain, the proposed RB system incorporates a built-in TIM, which modulates the beam's phase to achieve beam compression. To evaluate the compression performance, we utilize the beam spot radius, as defined in the previous chapter, analyzing its variations with respect to different structural parameters.

(1) Parameter Setting

The gain medium is composed of GaAsP semiconductor material, which generates light at a 980 nm wavelength. It is obliquely positioned 20 mm from M1. As detailed in Section 2.3 f_{r1} is set to infinity ($d = f$). To maintain par-axial beam propagation, the focal length f_{r2} of M2 is set as a variable. The TIM is positioned on the side of the gain medium, with its position parameter d_2 set to 20 mm relative to the gain chip. The concave lens within the TIM is designed with a focal length of $f_1 = -5$ mm. We investigate the impact of the end-to-end distance d_3 (ranging from 2 m to 10 m) and the TIM structure parameter M . Finally, given that the beam spot radius varies with distance, we utilize the maximum spot radius on the gain medium, $\omega_{g,Max}$, as a critical metric for evaluation.

(2) Calculation Results and Analysis

Figure 6a presents the calculated results, showing the relationship between the TIM structure parameter M and the maximum beam spot radius $\omega_{g,Max}$. As M increases, $\omega_{g,Max}$ exhibits a downward trend. Specifically, for M values ranging from 2 to 6, the beam radius rapidly decreases. For $M > 10$, the beam spot radius's decrease becomes more gradual, indicating a limited compression capacity. Moreover, for large values of M , the beam spot compression tends to stabilize. Furthermore, if the end-to-end distance d_3 is

large, $\omega_{g,Max}$ will increase. Quantitatively, the incident beam is compressed from 1.2 mm to approximately 0.1 mm, representing a compression factor of $12\times$. Figure 6b depicts curves of $\omega_{g,Max}$ as a function of d_3 . As shown, in the original scheme without TIM ($M = 1$), the beam radius increases significantly as d_3 increases. In contrast, the proposed scheme with TIM exhibits a more gradual increase. Numerically, the $\omega_{g,Max}$ value for the proposed scheme remains below 0.25 mm, whereas for the original scheme, it exceeds 0.5 mm. Furthermore, we analyze the influence of the focal length f_{r2} of reflector M2 on beam compression. Figure 7 shows the maximum beam radius on the gain medium as a function of f_{r2} . As depicted, $\omega_{g,Max}$ exhibits an upward trend as f_{r2} increases. Concurrently, the curves show a downward shift with an increase in M . Overall, an increase in f_{r2} tends to have a detrimental effect on beam compression, as evidenced by the enlargement of the beam spot.

From the aforementioned analysis, it can be preliminarily concluded that the TIM effectively compresses the beam across varying end-to-end distances. As discussed in Sections 2.1 and 2.2, this capability ensures that the resonant beam can enter the micron-sized semiconductor gain medium without significant energy loss.

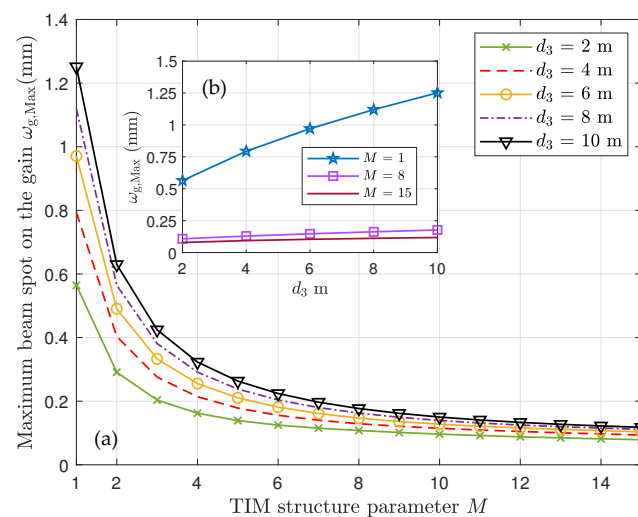


Figure 6. Maximum beam radius on the gain medium as a function of the TIM structure parameter M and transmission distance d_3 : (a) variation with M under different d_3 values; (b) variation with d_3 under different M values.

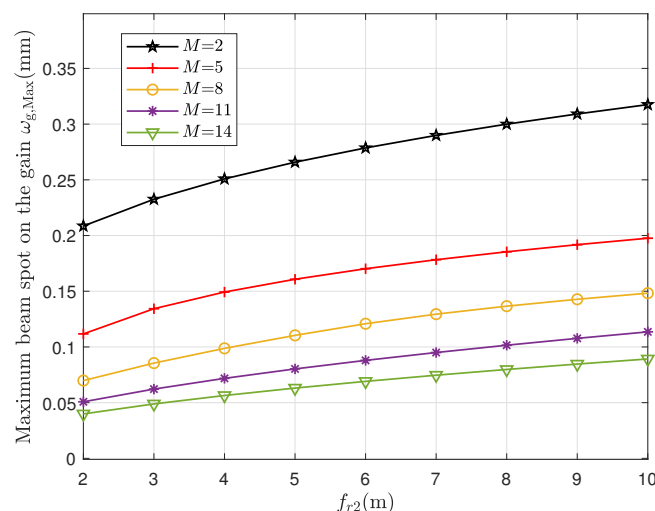


Figure 7. Maximum beam radius on the gain versus f_{r2} parameters of reflector M2 with different TIM structure parameters.

3.2. Received Beam Power

According to Section 2.1, after the energy accumulates, 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_{beam} to evaluate the end-to-end beam transmission performance.

(1) Parameter Setting

According to the material properties of GaAsP, we can obtain the characteristic parameters such as light quantum, gain factor, etc., as listed in Table 1. Furthermore, we adopt a typical laser diode as the pump source whose electro-optical conversion efficiency η_{pc} and absorption efficiency η_{pa} are 0.6 and 0.85. In addition, the effective active cross-section A_s of the gain is set as $3 \times 10^{-4} \text{ cm}^2$, the constant loss V_c is 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.

Table 1. Parameters of the gain medium [33].

Parameter	Symbol	Value
Gain factor	g_0	2000 cm^{-1}
Transparency carrier density	N_0	$1.7 \times 10^{18} \text{ cm}^{-3}$
Longitudinal confinement factor	Γ	2.0
Light speed	c	$3 \times 10^8 \text{ m/s}$
Planck constant	h	$6.6260693 \times 10^{-34} \text{ J}\cdot\text{s}$
Monomolecular recombination coefficient	α	10^7 s^{-1}
Bimolecular recombination coefficient	β	$10^{-10} \text{ cm}^3/\text{s}$
Auger recombination coefficient	γ	$6 \times 10^{-30} \text{ cm}^6/\text{s}$

(2) Calculation Results and Analysis

Figure 8 describes the relationship among the received beam power (P_{beam}), conversion efficiency (η_b), and the thickness of the effective gain layer (l). It is observed that as l increases, both P_{beam} and η_b exhibit a rising trend. However, this upward trend tends to plateau when the thickness of the effective gain layer reaches a larger value. Consequently, the influence of l on both P_{beam} and η_b becomes less pronounced. Moreover, when P_{in} takes a large value, curves of P_{beam} and η_b will move up. Numerically, the received beam power can be 60 W and beam conversion efficiency can be 40 % as $P_{\text{in}}=150 \text{ W}$, and the increase in P_{in} has a significant impact on P_{beam} but only a limited impact on η_b . Overall, by appropriately increasing the thickness, we can enhance the performance of beam transmission.

Figure 9 presents the curves of received beam power and conversion efficiency versus the reflectivity of M2. From the blue lines in the graph, it is evident that as the reflectivity of mirror M2 (R_2) 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 (P_{beam}) and the beam conversion efficiency (η_b) shift to the left and ascend. Numerically, the maximum value of P_{beam} and η_b are obtained when R_2 is in the range from 0.9 to 0.95.

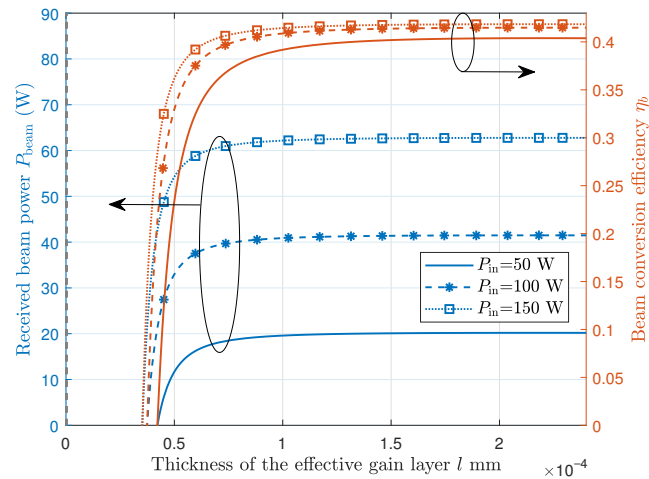


Figure 8. Received beam power and conversion efficiency versus thickness of the effective gain layer.

In Figure 10, we analyze P_{beam} and η_b as functions of the input power P_{in} . According to the blue lines, the P_{beam} increases as P_{in} increases, which presents a positive linear relationship with P_{in} . Moreover, the slope and intercept of lines are affected by R_2 . A large value of R_2 is beneficial for reducing the threshold power (line intercept). Besides, from the red curves, η_b is also enhanced as P_{in} increases. However, different from P_{beam} , the curves are nonlinear and gradually flatten out.

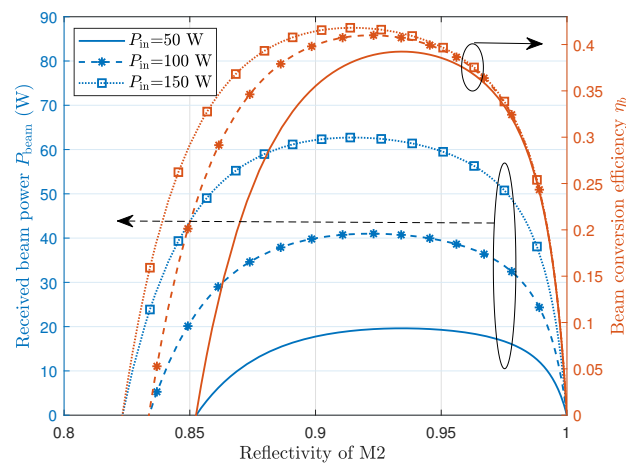


Figure 9. Received beam power and conversion efficiency versus reflectivity of M2.

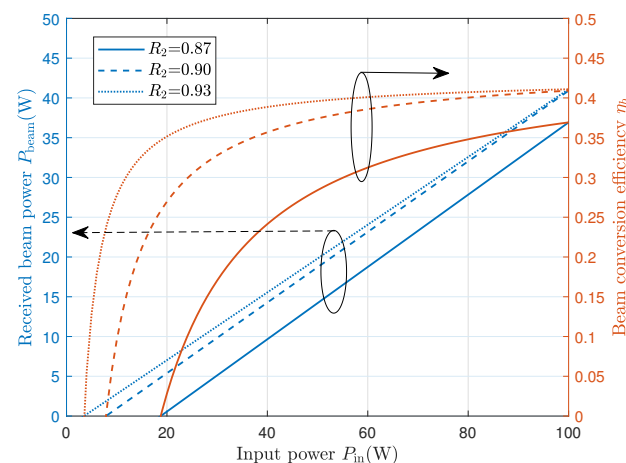


Figure 10. Received beam power and conversion efficiency versus input power.

Further, we evaluate the performance of received beam power P_{beam} as the function of transmission distance d_3 , which is shown in Figure 11. As can be seen, curves of P_{beam} present a downtrend with the increase in d_3 which proves the negative impact of the transmission loss on beam output (Section 2.3). Moreover, as the value of M increases, the curves become flatter. This indicates that the transmission loss can be suppressed by the TIM. Numerically, the value of P_{beam} can maintain 40 W output over a 15 m distance.

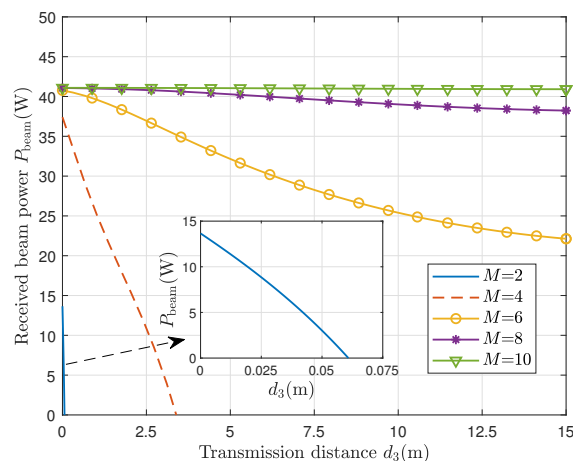


Figure 11. Received beam power versus transmission distance.

3.3. Output Electric Power and Channel Capacity

To evaluate the received beam power, we have examined the factors influencing both P_{beam} and η_b . Additionally, it is necessary to analyze the performance of the PV cell and the APD in the context of SWIPT.

(1) Parameter Setting

To evaluate the SWIPT performance, the PV and APD structure parameters should be defined. According to [39], PV cell structure parameters η_p and P_{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 1.6×10^{-19} C, and the Boltzmann constant k is 1.38×10^{-23} J/K. The APD for light signal receiving involves commercial sensors with 980 nm wavelength. Then, based on [41,43–45], we set the conversion responsivity of the APD $\nu = 0.6$ A/W, the noise bandwidth $B_x = 811.7$ MHz, the background current $I_{\text{bg}} = 5100$ μ A, and the load resistance $R_L = 10$ k Ω .

(2) Calculation Results and Analysis

Figure 12 depicts the curves of spectral efficiency, output electric power, and end-to-end conversion efficiency versus the beam splitting ratio. Observing the blue line, the entire curve exhibits a downward trend as μ increases. Initially, this decline is relatively gradual. However, when μ exceeds 0.8, $\tilde{C}$ starts to decrease sharply.

From the red and green lines with markers, it is evident that both P_{Eout} and η_E exhibit a positive linear relationship with μ . Their values increase as μ increases. Numerically, the spectral efficiency $\tilde{C}$ reaches 17.69 bit/s/Hz when μ is set to 0.99, at which point P_{Eout} and η_E are also high. Therefore, this value of μ can be chosen as the beam splitting ratio to achieve high-efficiency SWIPT.

In addition, we explore the relationship of spectral efficiency, output electric power, and end-to-end conversion efficiency versus input power, which is presented in Figure 13. From the blue line, it is 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_{in} is increased from 50 W to 150 W, the spectral efficiency experiences only a modest increase of 1 bit/s/Hz.

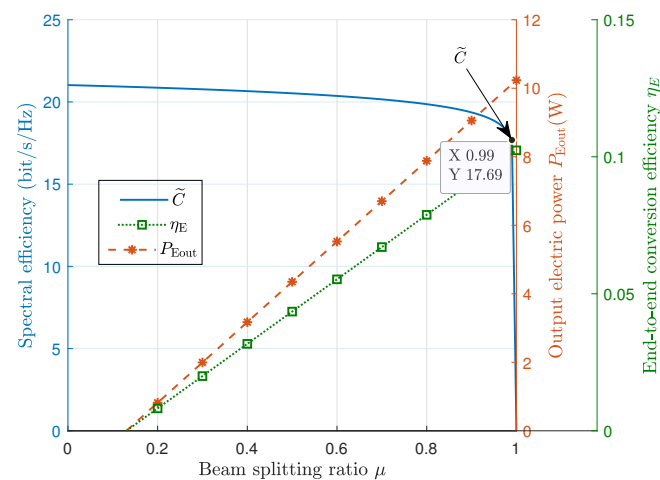


Figure 12. Spectral efficiency, output electric power, and end-to-end conversion efficiency versus beam split ratio ($P_{in} = 100$ W).

Furthermore, as indicated by the red and green lines in Figure 13, both P_{Eout} and η_E exhibit a positive relationship with P_{in} , where P_{Eout} shows a linear trend and η_E demonstrates a nonlinear one. Numerically, P_{Eout} and η_E can reach 16 W and 0.11, respectively, at $P_{in} = 150$ 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 output electric power. This demonstrates the system's potential for high-rate and high-power SWIPT.

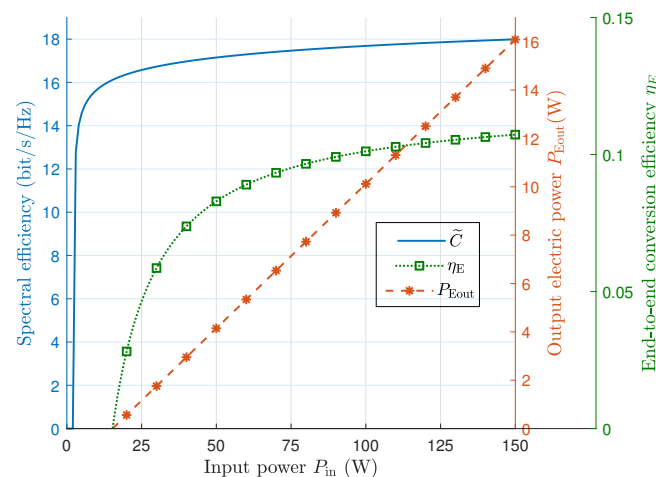


Figure 13. Spectral efficiency, output electric power, and end-to-end conversion efficiency versus input power ($\mu = 0.99$).

3.4. 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 2 presents the performance comparison between our system and the existing architectures, clearly demonstrating the advantages of the proposed RB SWIPT system in delivering high power, maintaining high spectrum efficiency,

and ensuring high energy conversion efficiency over long transmission distances. The improvement in end-to-end efficiency is not caused by a single factor. The semiconductor gain medium mainly reduces the threshold power and improves the pump absorption process. The TIM mainly reduces diffraction/aperture mismatch loss by compressing the beam spot on the gain medium. The output-coupler reflectivity R_2 further determines the tradeoff between intracavity buildup and useful beam extraction. Therefore, the predicted efficiency improvement is a combined result of the semiconductor gain medium, TIM-assisted beam compression, and output-coupling optimization.

Table 2. Comparison of existing SWIPT schemes.

Technology	Ref.	Conversion Efficiency	Spectral Efficiency	Output Power	Transmission Distance
Visible light	[46]	$0.38 \times 10^{-4}\%$	6 bit/s/Hz	2.96 mW	1.5 m
	[47]	$8.44 \times 10^{-5}\%$	8 bit/s/Hz	0.38 mW	3.0 m
Radio frequency	[48]	$1.375 \times 10^{-4}\%$	Not stated	5.5 μ W	15 m
	[49]	$5 \times 10^{-2}\%$	7 bit/s/Hz	5 mW	10 m
Resonant beam	[15]	1%	Not stated	2 W	2.6 m
	This work	11%	18 bit/s/Hz	16 W	15 m

The three most representative parameters are the output-coupler reflectivity R_2 , the TIM compression factor M , and the beam splitting ratio μ . First, R_2 determines the tradeoff between cavity feedback and useful output coupling, and it therefore strongly affects the resonant beam output power and beam conversion efficiency. Second, M changes the beam size inside the resonator and affects diffraction/aperture loss, especially when the resonant beam needs to be matched to the small semiconductor gain medium. Third, μ controls the power allocation between the PV module and the APD module. Increasing μ improves the harvested electric power and end-to-end conversion efficiency, but it reduces the optical power used for data reception and thus decreases the spectral efficiency.

4. Discussion

4.1. Transmission Model by Electromagnetic Field Propagation

In the aforementioned sections, we have developed an 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 [50]. Furthermore, according to the 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 [51]. 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 [52], as a criterion for stable output, we can determine the steady-state light field distribution.

Figure 14 presents the field distribution on the gain medium based on the electromagnetic field propagation model. As can be seen, the incident beam on the gain medium has been effectively compressed in the proposed system with TIM. In contrast, the beam has a broader field distribution and lower beam quality (uneven distribution) in the original system without TIM. This analysis corresponds to the results obtained using the matrix model in Section 5, further verifying the feasibility of our proposed scheme. Recent progress in structured laser modes also provides useful context for understanding mode control in laser resonators [53]. Overall, electromagnetic field propagation analysis is beneficial for evaluating the beam's quality, system structure, etc. However, it is 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.

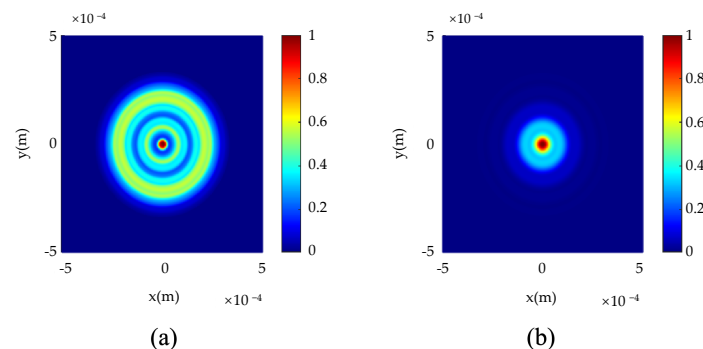


Figure 14. Field distribution on the gain medium: (a) without TIM; (b) with TIM.

4.2. Experimental Setup and Analysis

In this paper, we propose a high-efficiency RB charging and communication scheme, provide an analytical model, and evaluate system performance through simulation. To discuss the practical feasibility of the proposed scheme, we set up a preliminary optical test platform.

Figure 15 presents the setup photos of the experimental testbed. The testbed mainly includes reflectors, mirrors, telescope internal modulator (TIM), and the gain medium. As detailed in Section 2, the gain medium is responsible for generating photons through electro-optical conversion. The TIM, which consists of a series of lenses, compresses the incident beam to facilitate extended transmission distances. Beams are reflected by reflectors located at both the receiver and transmitter ends, oscillating back and forth in free space. Additionally, two mirrors with highly reflective coatings are placed on two optical workbenches to fold the light path to achieve equivalent transmission of tens of meters in an indoor environment. Utilizing infrared cameras for measurement, as depicted in Figure 15(b) by implementing a double-fold in the optical path using mirror, the system can demonstrate beam output at a distance of around 15 m. This achievement validates the system's efficacy in long-range energy transmission and output, in stark contrast to the original scheme, which was limited to only 2.6 m [15].

The experimental observations in Figure 15 provide preliminary support for the optical feasibility of the proposed resonant beam structure. Specifically, the platform confirms that the resonant beam cavity can be constructed and that the beam can be formed and observed after the folded optical path, which is consistent with the beam-transmission analysis in the preceding sections. The TIM-assisted optical layout also supports beam compression and long-distance beam propagation in the cavity. Therefore, the experiment provides qualitative validation of the cavity construction and beam-transmission feasibility assumed

in the analytical model. However, the present setup does not yet provide quantitative validation of the predicted output electric power, end-to-end conversion efficiency, or spectral efficiency.

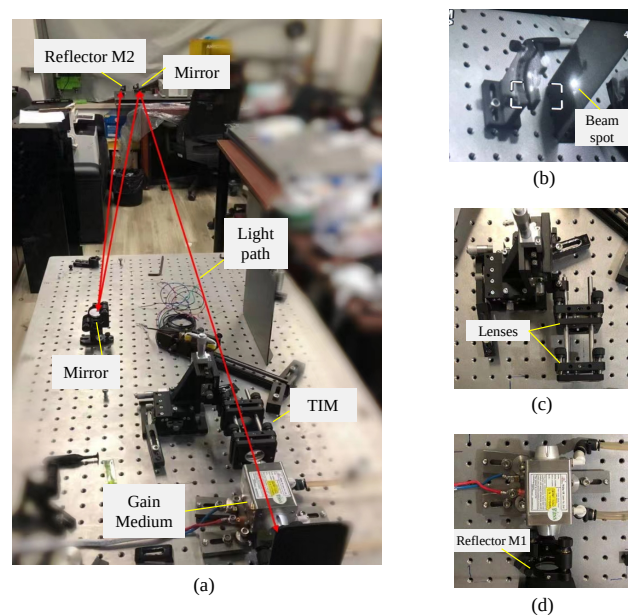


Figure 15. Experimental testbed: (a) platform overview, (b) beam output through the reflector M2 (detected by infrared camera), (c) TIM structure, and (d) gain medium and reflector M1.

4.3. Applications in IoT

As depicted in Figures 1 and 2, the RB-SWIPT can support several sensors or devices for IoT, such as UAV, smartphones, etc. For instance, the UAV's fuselage can be 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 m and a mere 1% conversion efficiency, as reported in [15]. 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 medium, 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.

5. Conclusions

In this paper, we 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 analysis of beam propagation, output beam power, output electric power, and spectral efficiency of our proposed system. Numerical results demonstrate that our system exhibits exceptional SWIPT performance. It is capable of producing 16 W of electric power 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) A more extensive experimental test platform can be established by incorporating both gain media and communication modules, which would enable a more thorough examination and analysis of the energy transfer capabilities and communication performance of the proposed system. (2) The implementation of the RB system in IoT sensors and devices, encompassing aspects such as module integration and load, along with its consequential impact on device performance parameters, such as power output and data transmission rates, can be further explored.

Author Contributions: Conceptualization, Y.B., M.X., and C.L.; methodology, Y.B. and J.K.; software, J.K.; validation, C.L.; formal analysis, M.X.; resources, X.W.; data curation, L.S.; writing—original draft preparation, Y.B.; writing—review and editing, Y.B., M.X., and L.S.; supervision, Q.L.; project administration, Q.L. and X.W.; funding acquisition, Q.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Authors Yunfeng Bai and Changsheng Li were employed by the company Shanghai Aerospace Electronics Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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