NLOS Transmission Analysis for Mobile SLIPT Using Resonant Beam

Mingqing Liu, Graduate Student Member, IEEE, Shuaifan Xia, Mingliang Xiong, Mengyuan Xu, Qingwen Liu, Senior Member, IEEE, and Hao Deng, Member, IEEE

Abstract—Simultaneous lightweight information and power transfer (SLIPT) is a potential way to meet the demands of sustainable power supply and high-rate data transfer in next-generation networks. Although resonant beam-based SLIPT (RB-SLIPT) can realize high-power energy transfer, high-rate data transfer, human safety, and self-alignment simultaneously, mobile transmission channel (MTC) analysis under non-line-of-sight (NLOS) propagation has not been investigated. In this paper, we propose analytical models and simulation tools for reflector-assisted NLOS transmission of RB-SLIPT, where transmission loss and accurate beam field profile of NLOS MTC can be obtained with a receiver at arbitrary positions and attitude angles. We establish analytical models relying on full diffraction theory for beam propagation between tilted or off-axis planes. Then, we provide three numerical methods (i.e., NUFFT-based, cubic interpolation-based, and linear interpolation-based methods) in simulations. Moreover, to deal with the contradiction between limited computing memory and high sampling requirements for long-range transmission analysis, we propose a multi-hop sliding window approach, which can reduce the sampling number by a factor of thousands. Finally, numerical results demonstrate that RB-SLIPT can achieve 3W charging power and 10bit/s/Hz data rate over a 2m distance in NLOS scenarios.

Index Terms—Resonant beam system, simultaneous lightweight information and power transfer, non-line-of-sight, tilted plane diffraction, fox-Li algorithm.

I. INTRODUCTION

W ith growing prosperity of applications in smart homes, smart industry, smart cities, etc., the number of Internet of Things (IoT) devices is growing exponentially [1]. Meanwhile, the high-rate data transfer and constant power supply are increasingly demanding. Utilizing the electromagnetic wave to deliver energy and data simultaneously has been investigated sufficiently [2]. Recently, research on simultaneous lightweight information and power transfer (SLIPT) has gained attention from both academia and industry due to its potential for higher data rates and low latency [3]. Among the existing SLIPT schemes which generally utilize light-emitting diode (LED) [4] or lasers [5] as the carrier, a resonant beam-based SLIPT (RB-SLIPT) scheme has been put forward to deal with the challenge of simultaneously realizing high transmission efficiency and self-alignment without beam-steering control [6]. However, along with the broader spectrum of light that offers extra bandwidths compared with radio frequency (RF), the nature of light requires that the path between the transceivers is not obstructed, which is referred to as the Line-of-Sight (LOS) requirement [7]. In this paper, we investigate the mobile transmission channel (MTC) performance of RB-SLIPT under non-line-of-sight (NLOS) propagation, which can enhance the system feasibility in the complex and dynamic environment.

Recently, considerable efforts have been put into system design and channel analysis for lightweight-based systems under NLOS propagation [8], [9], [10]. In some works, NLOS links are treated as disturbance sources, and the impact of NLOS propagation on visible light communication (VLC) channels is investigated [9]. To fully utilize the NLOS link and enhance system performance in the presence of various possible obstructions, the blocked light beam intuitively needs to be reflected to bypass the obstacle and reach the receiver. Thus, reflectors to manipulate the beam path, including single mirrors and mirror arrays, are deployed in SLIPT systems to establish an additional link for NLOS scenarios [11]. Specular reflections are generally adopted in such cases [12], [13], while diffuse reflection to convert the point-to-point optical link into a broadcast channel is also deployed in [14], [15], and [16]. However, scattered light from diffuse reflectors carries insufficient power for wireless charging IoT devices. Besides, regarding reflector-assisted NLOS link, intelligent reflecting surface (IRS) is introduced in VLC systems for significant performance enhancement [17]. Using the mirror array, metasurface, or liquid crystal switch and conduct reflector rotation, voltage control, or switch on and off, LOS requirements of SLIPT systems can be relaxed [18]. Moreover, optimization such as rate maximization can be achieved with optimization algorithm design in IRS-aided VLC systems [19], [20]. However, due to
With our proposed system design and laser photovoltaic (PV) panel for converting wireless charging high-rate data to receivers without echo interference and a second harmonic generation (SHG) crystal for delivering spatial positions and altitude angles. For SLIPT, we adopt analytical models for RB-SLIPT with a receiver at arbitrary positions and attitude angles. Hence, we propose MTC distance depends on the placement of reflector. Meanwhile, the receiver can be arbitrarily tilted. Hence, we propose analytical models for NLOS propagation of RB-SLIPT by analyzing the LOS channel with an off-axis receiver, where the off-axis beam field profiles utilizing the beam transmission simulation between non-coaxial and tilted planes [27], [28]. Further, we propose a multi-hop sliding window method to deal with the strict sampling requirements for long-range transmission posed by the accuracy improvement of NLOS link analysis.

The contributions of this manuscript are:

1) We propose analytical models for reflector-assisted NLOS transmission of RB-SLIPT, where the transmission loss and accurate beam field profile of MTC can be obtained. Based on the above models, we can analyze the energy/data transfer performance of RB-SLIPT with a receiver at arbitrary positions and attitude angles in NLOS scenarios.

2) We develop a computational approach with multi-hop sliding windows for long-range transmission simulation, which reduces the sampling number by a factor of thousands under 2m distance compared to original methods.

The remainder of this paper is organized as follows. In Section II, we describe the system architecture and formulate the problem of RB-SLIPT MTC analysis under NLOS propagation. In Section III, we present the analytical models, including the self-reproducing mode and transmission loss calculation as well as SLIPT design and performance evaluation, where the receiver can be arbitrarily placed. In Section IV, we present the implementation details during the computational process. In Section V, we demonstrate the RB-SLIPT performance with different moving states under NLOS propagation through numerical analysis. Finally, we conclude in Section VI.

II. PROBLEM FORMULATION

To present analytical models for NLOS transmission of RB-SLIPT, we first introduce the unique features of RB-SLIPT's MTC. Then we put forward the equivalent channel model of RB-SLIPT in NLOS scenarios and formulate the NLOS problem into MTC analysis with a simultaneously tilted and off-axis receiver in RB-SLIPT systems.

A. RB-SLIPT Structure and Feature

In Fig. 2 (a), RB-SLIPT consists of a spatially separated transmitter and receiver, which jointly form a resonant cavity, i.e., MTC. The resonant beam generated within the MTC acts as the carrier of energy or data transferring over the air, which is essentially an intra-cavity laser. The generation of the resonant beam, i.e., the establishment of RB-SLIPT’s MTC, can be expressed by principles of working of a laser - lasers are
continuously cause damage. Thus, the high-power beam will not cease immediately. Thus, the high-power beam will not be destroyed, and the resonant beam established. Moreover, if there is a foreign object, i.e., human transmitter, the receiver is self-aligned, and the MTC is self-aligned. Words, if the RB-SLIPT receiver is within the FoV of the transceivers are not strictly faced with each other. In other words, the resonant cavity can pass the gain medium multiple times to be amplified. Once the amplification of the photons can compensate for the total losses including transmission loss in the channel and output loss at the receiver, a stable resonant beam can be established automatically. For SLIPT, retroreflector at the receiver is transmissive and output extra-cavity laser is collected by PV panel and photodiode (PD) for energy and data harvesting.

The above channel establishment process brings two unique features: self-alignment and safety. Retroreflectors can reflect beams from any direction back along the incoming path. With two retroreflectors embedded respectively in the transmitter and receiver, the resonant beam can be generated even if the transceivers are not strictly faced with each other. In other words, if the RB-SLIPT receiver is within the FoV of the transmitter, the receiver is self-aligned, and the MTC is self-established. Moreover, if there is a foreign object, i.e., human hands, invading the MTC, the generation condition of the resonant beam will be destroyed, and the resonant beam will cease immediately. Thus, the high-power beam will not continuously cause damage.

The power flow in RB-SLIPT is also depicted in Fig. 2 (a). $P_{\text{in}}$ from the input source is given to the gain medium, and the electrical power is converted to beam power. Then, after transferring over the air with transmission losses, the laser beam is output with power $P_{\text{out}}$. Finally, the electrical power converted by PV and data rate from PD can be analyzed. As the power conversion at transceivers can be evaluated by linear models, obtaining accurate transmission loss of the RB-SLIPT channel is crucial for analyzing SLIPT performance [29], [30], [31], [32].

**B. NLOS Transmission Analysis**

Obviously, RB-SLIPT is sensitive to blockage due to features of MTC. However, even under NLOS propagation, there are still ways to satisfy the conditions for the self-establishment of MTC. That is, if we construct a loop so that the resonant beam can still travel back and forth within the resonant cavity and pass through the gain medium with the assistance of an additional reflector, the resonant beam can be generated with sufficient input source to the gain medium. As in Fig. 2 (b), an obstacle blocks the MTC between the transmitter and receiver. Attach a reflector to the wall beneath the original MTC, a resonant beam is generated within a channel formed by a transmitter, reflector, and receiver.

We build a coordinate system to illustrate the NLOS transmission of RB-SLIPT as in Fig. 2 (b), where we take the resonant cavity with two cat’s eye retroreflectors (CRRs) as an example. CRR consists of a lens with focal length $f$ and a mirror of which the radius are both $r_c$. The origin of the coordinate system is consistent with the center of the mirror of the CRR1 in the transmitter, and the x-axis coincides with its surface. Moreover, the z-axis is perpendicular to the original MTC, a resonant beam is generated within a channel formed by a transmitter, reflector, and receiver.

Above all, the MTC analysis of RB-SLIPT under NLOS propagation can be deduced to the analysis under LOS propagation with the transmitter but tilts $\phi'$ on the y-axis. Correspondingly, the tilt angle of the mirror-symmetrical CRR2' is $\phi'= -\phi$. Above all, the MTC analysis of RB-SLIPT under NLOS propagation can be deduced to the analysis under LOS propagation with a receiver: i) tilts $\phi''$ on the x-axis and ii) off the z-axis by $s_z$ depending on the reflector’s placement. Transmission loss varies with different $\phi''$ and $\Delta x$, which we can use for estimating the NLOS channel of RB-SLIPT.

Thus, the NLOS transmission analysis problem in RB-SLIPT is formulated as finding the transmission loss of the LOS channel given the position and attitude angle of receiver $(s_x, s_y, s_z, \phi')$ relative to the transmitter. Besides, we can obtain $P_{\text{out}}$ of RB-SLIPT with the transmission loss for the following SLIPT performance analysis.

\[ h \leq r_c s_z / 2 f. \]  

Then, CRR2' is equivalent to being shifted away from the z-axis by $s_z = 2h$ on the x-axis (y-axis in the same manner).

Moreover, we demonstrate the NLOS transmission analysis with a receiver at an arbitrary attitude angle, which is common in real application scenarios. As in Fig. 2 (b), CRR2 is coaxial with the transmitter but tilts $\phi'$ on the y-axis. Correspondingly, the tilt angle of the mirror-symmetrical CRR2' is $\phi' = -\phi$. Above all, the MTC analysis of RB-SLIPT under NLOS propagation can be deduced to the analysis under LOS propagation with a receiver: i) tilts $\phi''$ on the x-axis and ii) off the z-axis by $s_z$ depending on the reflector’s placement. Transmission loss varies with different $\phi''$ and $\Delta x$, which we can use for estimating the NLOS channel of RB-SLIPT.

Thus, the NLOS transmission analysis problem in RB-SLIPT is formulated as finding the transmission loss of the LOS channel given the position and attitude angle of receiver $(s_x, s_y, s_z, \phi')$ relative to the transmitter. Besides, we can obtain $P_{\text{out}}$ of RB-SLIPT with the transmission loss for the following SLIPT performance analysis.
between the plane of gain medium (we name it as the source plane) and the tilted plane of lens L2. The tilted plane is \( s_z \) distance away from the source plane, and the tilted angle is \( \varphi^o \). The calculation of beam transfer between these two planes is summarized as follows [27], [28].

The beam field first propagates to a reference plane \((x_1, y')\) parallel to the source plane, which shares the same origin as the tilted plane. Given the spatial beam field distribution on source plane \( U(x, y, 0) \), we can get the angular spectrum of beam field \( A_d(f_x, f_y) \) on the reference plane as [31]

\[
A_d(f_x, f_y) = \mathcal{F}\{U(x, y, 0)\} \cdot H(f_x, f_y, s_z),
\]

where \( \mathcal{F} \) indicates the fast Fourier transform (FFT) process and \( H(f_x, f_y, s_z) \) is the free space transfer function as [31]

\[
H(f_x, f_y, s_z) = \exp \left[ \frac{2\pi s_z}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right].
\]

where \( \lambda \) is wavelength and \((f_x, f_y)\) is the spectrum coordinate.

Next, to obtain the spatial beam field distribution on the tilted plane, we should map \( A_d(f_x, f_y) \) to the angular spectrum of beam field on tilted plane \( A'_d(f'_x, f'_y) \) by coordinate conversion. The relationship between the two angular spectra is represented as (see Appendix for details) [27]

\[
A'_d(f'_x, f'_y) = A_d(\cos \varphi f'_x + \sin \varphi f'_y, f'_y),
\]

where \( w'(f'_x, f'_y) \) can be depicted as

\[
w'(f'_x, f'_y) = \sqrt{\lambda^2 - f_x'^2 - f_y'^2},
\]

where \((f'_x, f'_y)\) is the spectrum coordinate on tilted plane.

Finally, we can calculate the beam field distribution on the tilted plane. Since the transform in Eq. (31) is not linear, the spectrum after the rotation will become non-uniform sampled, leading to energy loss. Hence, we cannot obtain the beam field with the original inverse FFT (IFFT) imposed on \( A'_d(f'_x, f'_y) \). We adopt the following two methods to deal with this issue.

I. Perform Type-I non-uniform Fourier transform onto \( A'_d(f'_x, f'_y) \) to transform a non-uniform spectrum input to a uniform sampled beam field distribution as [33] and [34]

\[
U(x', y', s_z) = \text{NUFFT}_1 \{ A'_d(f'_x, f'_y) \},
\]

where \text{NUFFT}_1 \ indicates the Type-I non-uniform Fourier transform process.

II. Apply interpolation onto the non-uniform \( A'_d(f'_x, f'_y) \) to obtain the uniform-sampled spectrum distribution, and compensate the energy loss by multiplying with an energy loss function \( J(f'_x, f'_y) \). Then, employ the ordinary IFFT to obtain a uniform beam field on the tilted plane as [27]

\[
U(x', y', s_z) = \mathcal{F}^{-1} \left\{ A'_d(f'_x, f'_y) \times J(f'_x, f'_y) \right\} \times \exp \left[ i2\pi f_{x0}s_z \right],
\]

where \( \mathcal{F}^{-1} \) indicates the IFFT process, \( \exp \left[ i2\pi f_{x0}s_z \right] \) represents shifting the center frequency \( f_{x0} \) back to zero by constructing a new coordinate system \( f_x = f'_x - f_{x0} \). Coordinate conversion in Eq. (4) leads to a spectrum central frequency displacement, which poses a problem for FFT as the frequency center is far from zero.
2) Self-Consistent Equation for Round-Trip Transmission: As in Fig. 4, we build the self-consistent equation for round-trip transmission of resonant beam: the beam field \( U(x, y) \) starts from mirror M1 in CRR at the transmitter, passes through all optical elements and free spaces between elements, then transfers back along the path from receiver to the transmitter, and finally arrives at M1 again [35]. For simplicity, we denote propagation operators \( \mathcal{A}, \mathcal{B}, \mathcal{C}, \mathcal{D}, \mathcal{E} \) indicating beam transmission through the mirror, gain medium, lens, free space between mirror and lens, and free space between the lens and gain medium, respectively, which are specified as follows [35]:

\[
\begin{align*}
\mathcal{A}[U(x, y)] &= U(x, y) \cdot \begin{cases} 
1, & x^2 + y^2 \leq r_c^2 \\
0, & \text{else}
\end{cases} \\
\mathcal{B}[U(x, y)] &= U(x, y) \cdot \begin{cases} 
1, & x^2 + y^2 \leq r_g^2 \\
0, & \text{else}
\end{cases} \\
\mathcal{C}[U(x, y)] &= U(x, y) \cdot e^{-\frac{x^2 + y^2}{2r_c^2}}, \quad x^2 + y^2 \leq r_c^2 \\
\mathcal{D}[U(x, y)] &= \mathcal{F}^{-1}\left\{\mathcal{F}\{U(x, y)\} \cdot H(f_x, f_y, l)\right\}, \\
\mathcal{E}[U(x, y)] &= \mathcal{F}^{-1}\left\{\mathcal{F}\{U(x, y)\} \cdot H(f_x, f_y, f)\right\},
\end{align*}
\]

(8)

where \( r_c \) and \( r_g \) represent the radius of CRR and gain medium, respectively. \( f \) is the focal length of L1/L2 and \( l \) is the interval between M1/M2 and L1/L2.

For beam propagation between gain medium and L2, we denote \( \mathcal{P}_t \) to represent the calculation process of Eqs. (2), (4), and (6) or (7). With the beam field on gain medium plane \( U_G(x, y, f + l) \), we obtain beam field on left side of L2 as

\[
U_{L2}(x, y, s_z + 2f + l) = \mathcal{P}_t[U_G(x, y, f + l)].
\]

(9)

However, for the opposite transfer direction, we calculate the beam propagation from a tilted plane, where we denote the \( \mathcal{P}_t^{-1} \) for the inverse calculation process. Similarly, two ways to get the beam field on the gain medium plane are as follows.

I. Perform NUFFT1 onto \( U_{L2} \) to transform a uniform sampled beam field input to a non-uniform spectrum distribution, and then map the obtained spectrum distribution to the reference plane parallel to gain medium plane by Eq. (4) with \( -\varphi_0 \). Then, after multiplying with the free space transfer function \( H(f_x, f_y, s_z + f) \), \( U_G(x, y, f + l) \) is obtained by IFFT.

II. Perform FFT onto \( U_{L2} \) and conduct coordinate mapping with \( -\varphi_0 \) by applying interpolation to obtain the uniform-sampled spectrum distribution. Then, after multiplying with \( H(f_x, f_y, s_z + f) \), \( U_G(x, y, f + l) \) is obtained by employing the ordinary IFFT as Eq. (7).

Finally, denoting \( \mathcal{R} = \mathcal{D}\mathcal{A}\mathcal{D}\mathcal{C} \) and \( \mathcal{T} = \mathcal{B}\mathcal{E}\mathcal{C}\mathcal{D} \) for simplicity, we build a self-consistent equation for round-trip transmission of the resonant beam with a receiver tilted as

\[
U(x, y, 0) = \mathcal{T}^{-1}\mathcal{P}_t^{-1}\mathcal{R}\mathcal{P}_t\mathcal{T}[U(x, y, 0)].
\]

(10)

B. Receiver at Arbitrary Spatial Position

Then, we present the model for analyzing the MTC with a receiver at arbitrary spatial positions. As in Fig. 5 (a), CRR at the receiver is off-axis relative to transmitter. Here we consider
the receiver moves away from the z-axis along the x-axis with  

\begin{equation}
\begin{aligned}
x' &= x - s_x, \quad y' = y - s_y, \quad z' = s_z.
\end{aligned}
\end{equation}

Then, the beam field on the off-axis plane is derived as [28]

\begin{equation}
\begin{aligned}
U(x', y', z') &= \mathcal{F}^{-1}\{A_0'(f_x, f_y)\} H(f_x, f_y, s_z) \\
A_0'(f_x, f_y) &= \mathcal{F}\{\{U(x, y, 0)\} \exp[\imath 2\pi (f_x s_x + f_y s_y)]\},
\end{aligned}
\end{equation}

where $A_0'(f_x, f_y)$ is the shifted spectrum distribution. Thus, spectrum distribution on the shifted plane can be obtained by multiplying the original spectrum distribution by a phase shift proportional to the spatial displacement.

2) Self-Consistent Equation for Round-Trip Transmission: As shown in Fig. 5, calculations of the resonant beam traveling through mirrors, lenses, the gain medium, and the corresponding free spaces are the same as calculations we derived for circumstances with a tilted receiver. Yet the only difference is the transmission between the gain medium and L2 since they are non-coaxial to each other. We define operators $P_o$ and $P_o^{-1}$ to represent the beam transmission from gain medium to L2 and from L2 to gain medium in the following [35]:

\begin{equation}
\begin{aligned}
P_o[U(x, y)] &= \mathcal{F}^{-1}\{\mathcal{F}\{U(x, y)\} H(f_x, f_y, s_z + f) \\
&\quad \times \exp[\imath 2\pi (f_x s_x + f_y s_y)]\},
\end{aligned}
\end{equation}

\begin{equation}
\begin{aligned}
P_o^{-1}[U(x, y)] &= \mathcal{F}^{-1}\{\mathcal{F}\{U(x, y)\} H(f_x, f_y, s_z + f) \\
&\quad \times \exp[\imath 2\pi (-f_x s_x)]\}.
\end{aligned}
\end{equation}

Thus, the self-consistent equation for MTC with a receiver at arbitrary positions is built referring to Eq. (10) as

\begin{equation}
\begin{aligned}
U(x, y, 0) &= T^{-1}P_o^{-1}RP_o T[U(x, y, 0)].
\end{aligned}
\end{equation}

C. Self-Reproducing Mode and Transmission Loss

For MTC analysis of RB-SLIPT under NLOS propagation, as shown in Fig. 2, analytical models for the receiver at both tilt and off-axis states should be adopted. Stated that the calculation of beam transmission to a tilted plane is supposed to be conducted before the transmission to an off-axis plane [27], [28]. Moreover, the reflectivity and placement of the reflector adopted in the NLOS link affect channel performance. Suppose the amplitude reflectivity of the reflector M3 is $\gamma_3$, the self-consistent equation for NLOS transmission of the resonant beam is expressed by

\begin{equation}
\begin{aligned}
U = \gamma T^{-1}P_o^{-1}R P_{\gamma_3} T[U],
\end{aligned}
\end{equation}

where the placement of the reflector $h$ affects channel performance by introducing different off-axis distances as $s_x = 2h$ on the operator $P_o$. Moreover, $\gamma$, named as transmission factor, indicates the amplitude attenuation of the resonant beam field after one round-trip transmission, which we regard as over-the-air transmission efficiency of NLOS link for RB-SLIPT.

To obtain transmission factor $\gamma$, we should find the solutions of the self-consistent equations Eq. (16). With the Fox-Li method, we can obtain the self-reproducing mode and $\gamma$ of RB-SLIPT’s NLOS transmission channel by iterating Eq. (16). Given an arbitrary plane wave distribution $U$ as input and sufficient iteration times, the stable resonant beam mode can be formed where only amplitude difference occurs between distributions of each two iterations [32]. Suppose the self-reproducing mode $U_i(x, y)$ is formed at $t$-th iteration, transmission factor $\gamma$ is defined as [36]

\begin{equation}
\begin{aligned}
\gamma = \frac{||U_{t+1}(x, y)||}{||U_{t}(x, y)||},
\end{aligned}
\end{equation}

where $||\cdot||$ represents the $\ell_1$ norm, leading to the calculation of the sum of the absolute values of each element in the vector. According to laser cavity characteristics, transmission loss is expressed by loss = $1 - |\gamma|^2$.

D. Achievable Data Rate and Charging Power

We adopt a circular output laser power model as in Fig. 6 (a) illustrating the relationship between input pump power and output power for the following SLIPT performance evaluation, which has also been verified by testbed measurements of resonant beam systems [35], [36]. In Fig. 6 (a), $P_1 \sim P_4$ depict the beam intensity within the MTC, which grows after the multiplication of gain medium and decreases by free-space transmission loss factors $\gamma_1 \sim \gamma_4$ (=1-loss). $\gamma_1 \sim \gamma_4$ indicate transmission losses from CRR1 to gain medium, from gain medium to CRR2, from CRR2 to gain medium, and from gain medium to CRR1, respectively, which can be calculated directly after obtaining the self-reproducing mode [36]. Then, we can calculate the output power $P_{out}$ at the receiver as [36]

\begin{equation}
\begin{aligned}
P_{out} &= \frac{A_h I_S \gamma_2 \left(1 - R_2\right) \cdot \left[g_0 \ell - \ln \sqrt{R_E R_2 \gamma_3 \gamma_4}\right]}{1 - R_2 \gamma_3 \gamma_4 + \sqrt{R_E R_2 \gamma_3 \gamma_4} \left[1 / (\gamma_1 \gamma_2 \gamma_3) - \gamma_4\right]} \\
g_0 \ell &= \frac{\eta_{excit} P_{in}}{A_g I_S},
\end{aligned}
\end{equation}

where $\eta_{excit}$, $\eta_h$, $A_g = \pi r_g^2$, $I_S$ are the excitation efficiency, overlap efficiency, cross-sectional area, and saturation intensity of the gain medium; $\gamma_3$ is the internal loss generated in the gain medium; $P_{in}$ is the pumping power for gain medium.
to stimulate photons. $A_b$ is the cross-sectional area of the resonant beam which can be obtained by calculating the area of the self-reproducing mode. $R_2$ is the reflectivity of M2 in CRR2. Although the reflectivity $R_1$ of M1 is 100%, we adopt an SHG crystal for generating communications beams which will cause internal loss, we denote $R_E$ as the equivalent reflectivity of M1, where

$$ R_E = (1 - \eta_{SHG})^2 \Gamma_{SHG} R_1, \quad (19) $$

where $\eta_{SHG}$ is SHG efficiency representing the resonant beam power attenuation in the SHG process and $\Gamma_{SHG}$ is the transmittance of SHG.

Figure 6 (b) depicts the energy and data flow in RB-SLIPT with the communication scheme using the second harmonic of resonant beam [25], [26]. Resonant beam with 1064-nm wavelength transfers within the MTC, and 532-nm frequency-doubled beam is generated as resonant beam incidents on SHG. Through specifically designed coatings on each element’s surface, only 532-nm beam can pass through an electro-optic modulator (EOM) to be modulated with signals $\nu_{sig}(t)$. Besides, 532-nm beam can only transfer from SHG to the receiver without being reflected. Thus, the resonant beam reflected back and forth within MTC doesn’t carry modulated signal and will not affect the gain medium and modulation process, avoiding the echo interference [25], [26]. At the receiver, we use a beam splitter with a frequency-selective coating to separate 532-nm communication carrier and 1064-nm resonant beam. The communication carrier is reflected by the beam splitter and collected by PD while the resonant beam passes through the beam splitter to PV for electrical power conversion.

Regardless of transmission loss on lenses and gain medium, beam power for communications $P_{out,IT}$ is depicted as [25]

$$ P_{out,IT} = \Gamma_{PD} R_{BS}^2 \left( 1 - R_2^2 \right) R_3^2 \gamma_1 \gamma_2 \varepsilon \eta_{SHG} P_d $$

$$ P_c = 2 \eta_{SHG} P_{out} $$

$$ P_d = \gamma_1 \gamma_2 \varepsilon \eta_{SHG} R_{BS}^2 \left( 1 - R_2^2 \right) $$

$$ \eta_{SHG} = \frac{8 \pi^2 d_{eff}^2 \nu_{sig}(t)^2}{\varepsilon_0 c \lambda^2 n_0^2 A_b}, \quad (20) $$

where $\Gamma_{PD}$ is the ratio of power received by the PD to the total incident power, $R_{BS}^2$, $R_2^2$, and $R_3^2$ is the reflectivity of the beam splitter, M2 and reflector in NLOS link for frequency-doubled beam, respectively. $\varepsilon_0$ is the vacuum permeability; $d_{eff}$, $\nu_{sig}(t)$, and $n_0$ are the efficient nonlinear coefficient, thickness, and refractive index of SHG crystal, respectively [25].

Considering restrictions on limited energy resources and safety issues, we assume the ratio of average received power to peak signal power lies in the range of $[0.5, 1]$ while $P_{out,IT}$ represents the peak signal power [37]. Then, the achievable data rate of RB-SLIPT, referring to the lower-bounded channel capacity, can be expressed as [38] and [39]

$$ R_b = \frac{1}{2} \log_2 \left( 1 + \frac{(\rho_{PD} P_{out,IT})^2}{2 \pi e \sigma^2 n} \right) $$

$$ \sigma^2_n = 2 q (\rho_{PD} P_{out,IT} + \rho_{bk}) B + \frac{4 kT B}{R_{IL}}, \quad (21) $$

where $\rho_{PD}$ is the responsivity of PD, $e$ is the nature constant, and $\sigma^2_n$ is the total noise variance. $I_{bk} = 51000 \mu A$ is the photon current induced by background radiation, $B = 800$ MHz is the bandwidth, $k$ is Boltzmann constant, $T$ is the temperature in Kelvin, and $R_{IL}$ is the load resistance of the PD.

For energy transfer, we adopt an equivalent circuit model of the PV panel as in Fig. 7, where the conversion from beam power incidents on it to charging power $P_{chg}$ can be depicted as the following equations [40]

$$ P_{out,IT} = \Gamma_{PV} \Gamma_{BS} P_{out} $$

$$ I_{chg} = \rho_{PV} P_{out,IT} - I_d - \frac{V_d}{R_{sh}} $$

$$ I_d = I_0 \exp \left( \frac{qV_d}{n_s n_k T} - 1 \right) $$

$$ V_d = I_{chg} (R_{PL} + R_s) $$

$$ P_{chg} = I_{chg}^2 R_{PL}, \quad (22) $$

where $\Gamma_{PV}$ and $\Gamma_{BS}$ are the received power ratio of PV and transmittance of the beam splitter for resonant beam, respectively. $\rho_{PV}$ is the responsivity of PV, $I_d$ and $V_d$ are current and voltage passing through and on the diode, $I_0$ is the reverse saturation current, $n$ is the diode ideality factor, and $n_s$ is the number of series-connected cells. $R_{PL}$ is the load resistance, and $R_{sh}$ and $R_s$ are shunt resistance and series resistance in the equivalent circuit model.

IV. IMPLEMENTATION FOR ANALYTIC MODELS

Discretization of self-consistent equations is needed for implementing MTC analysis, where the sampling number requirements are essential. After summarizing the sampling requirements imposed by the different receiver’s moving, we present a specific design for implementing long-range transmission with an off-axis receiver, which can reduce the required sampling number and achieve feasibility.

A. Sampling Requirements

1) Aliasing Error and Interval Choosing: Correct sampling avoids aliasing during implementations. To eliminate the aliasing introduced by sampling the free space transmission function as Eqs. (2) and (3), the angular spectrum $A(f_x, f_y)$ needs to be cut off with an ideal low-pass filter based on the band-limited angular spectrum method. Suppose the cutoff frequency is $f_{lim}$, the spatial frequency needs to satisfy [33]

$$ -f_{lim} < f_x < f_{lim}, \quad -f_{lim} < f_y < f_{lim}. \quad (23) $$
\( f_{\text{limit}} \) is determined by Nyquist’s theorem as \[ f_{\text{limit}} = \frac{1}{\lambda[(2s_z \Delta f)^2 + 1]^{1/2}} \] where \( s_z \) is the transmission distance along the z-axis and \( \Delta f \) is the frequency sampling interval.

Besides, we also surround the aperture with zero elements with the window expanding factor for eliminating aliasing as in Fig. 8. However, sampling the spectrum distribution is essentially duplicating the computational window due to the periodicity of FFT. A large tilting angle or shifting distance will result in a spectrum shift to the neighboring windows, leading to aliasing. Hence, a sufficiently large computational window is needed to ensure no aliasing is introduced. Taking the spatial frequency on the x-axis to exemplify, the relation between sampling interval and tilting angles is \[ \Delta x \leq \frac{1}{2|\cos(\varphi)f_x - \sin(\varphi)f_z|} \] for \( f_x \in [-f_{\text{limit}}, f_{\text{limit}}] \), where \( f_z = \sqrt{(1/\lambda)^2 - f_x^2} \). For simulating beam transmission angle in \([-90^\circ, 90^\circ]\), the sampling interval should satisfy \( \Delta x \leq \lambda/2 \) [28], [33], [34].

2) Requirements Imposed by Long-Range Transmission: To comply with the transmission characteristics and application scenarios of RB-SLIPT, we may need to simulate transmission to a receiver with long-range (in terms of meters) and large relative angles (greater than \(10^\circ\)). Under such circumstances, the plane of the gain medium on the transmitter’s side is remote from the plane where L2 resides. As shown in Fig. 8, assume that there is a certain angle \( \theta \) between the transceivers, the z-axis distance \( s_{z1} \) between them corresponds to an off-axis shift \( s_{x1} \) on the receiver. By increasing the distance to \( s_{z2} \), the off-axis shift will be proportionally enlarged to \( s_{x2} \). However, with the increase of the z-axis distance, the off-axis shift will exceed the margin of the computational window. Consequently, the correct beam field distribution can hardly be perceived on the receiver, whereas the next period of the beam field will occur due to the periodicity of FFT.

This problem can be alleviated to some extent by increasing the computational window. Nevertheless, the sampling number will simultaneously grow significantly considering the sampling accuracy, leading to higher computational expense or even exorbitant memory consumption. To address the restrictive relation between the transmission distance and the size of the computational window, we propose a multi-hop sliding computational window design to achieve the long-range MTC analysis without increasing the computational window.

B. Design of Multi-Hop Sliding Computational Window

The scheme of the sliding computational window is illustrated in Fig. 8. Assuming the distance between transceivers is \( s_{z2} \), the off-axis shift \( s_{x2} \) of the receiver plane grows beyond the margin of the computational window for the transmitter plane. We can separate \( s_{z2} \) into several shorter distances \( s_{z1} \), and divide the free space transfer process into a series of transmissions between the intermediate planes. With the same \( \theta \), the first intermediate plane has an off-axis shift \( s_{x1} = s_{x2}s_{z1}/s_{z2} \) with respect to the transmitter’s plane, and the second intermediate plane has the same shift relative to the first intermediate plane, and so on. By judiciously selecting \( s_{z1} \), we can make sure that \( s_{x1} \) falls within the computational window. Thus, memory insufficiency and exorbitant computational requirements can be eliminated by confining the window size by introducing more intermediate planes.

Denote the window expansion factor as \( w \), the computational window size for CRR1 and CRR2 is \( 2w\Delta t \). Then, we deduce the relation between the computational window size, off-axis distance, and z-axis distance as follows

\[
\begin{align*}
    s_{x2} &= s_{z2} \tan \theta \\
    s_{z1} &= 2s_{x1}/s_{x2} \\
    s_{x1} &\leq w\Delta t.
\end{align*}
\]

For calculating the long-range transmission from the gain medium to a tiled and off-axis receiver, we first calculate the parallel transmission between the gain medium and each intermediate plane using the multi-hop sliding window method.
Meanwhile, we handle tilt first for the transmission from the last intermediate plane to the receiver where there is both offset and tilt, as illustrated in Eq. (16). For the opposite transmission from a tilted receiver to gain medium, we first calculate transmission from the tilted plane, then parallel transmission between intermediate planes and gain medium plane.

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we first specifically analyze how the tilted angle of the receiver influences the MTC, which is reflected by the transmission factor with different system parameters. Meanwhile, we depict the corresponding computational time for one round-trip transmission with different system parameters except for transmission loss. Moreover, similar conclusions would be drawn with different implementation methods. Thus, we choose \( \{ w = 2, N_s = 8192 \} \) as \( \{ r_c = r_g = 1 \text{mm}, f = 5 \text{mm} \} \), and \( \{ w = 2, N_s = 16384 \} \) as \( \{ r_c = r_g = 2 \text{mm}, f = 10 \text{mm} \} \), which satisfy the FFT calculation requirements and show NLOS MTC analysis with a receiver at different spatial positions and altitude angles. Besides, the Fox-Li iteration stops as the difference of the beam field distributions between two iterations is below \( 10^{-3} \). For evaluating NLOS transmission performance, we conduct experiments presenting impacts of the characteristics of reflector M3, i.e., reflectivity \( \bar{R}_3 \) and placement height \( h \). Finally, we perform experiments with different SHG thicknesses and PV equivalent circuit model parameters, which are fitted values from measurements on a real laser PV product [41], [43] for depicting SLIPT performances under NLOS transmission. Moreover, we neglect the transmission loss as the beam passes through lenses or gain medium within MTC. The parameters for SLIPT performance analysis are detailed in Table I.

### B. Receiver at Arbitrary Attitude Angle

As calculating the beam transmission between apertures with mm-level size over m-level distance poses challenges on large sampling numbers, we evaluate computational time with different implementation methods except for transmission loss. Figure 9 depicts the changing trend of both transmission factor \( \gamma \) and computational time for one round-trip transmission with the increase of tilted angles under different cat’s eye sizes and z-axis transmission distances. As illustrated above, there are three numerical methods simulating the beam propagation between tilted planes, i.e., NUFFT, cubic interpolation, and linear interpolation. For a cat’s eye with the stated parameters in Fig. 9 (a), the maximum allowable tilt or translation angle is around \( 10^\circ \). As the tilted angle increases, the transmission factor decreases and reduces to nearly zero at the tilted angle of \( 10^\circ \). Changing trend under the above three methods is similar, while the results under NUFFT and cubic interpolation are in good agreement. Meanwhile, the cubic and linear interpolation methods show better time-saving. Similar experiments are conducted as Figs. 9 (b) and (c) with \( r_c = r_g = 2 \text{mm} \), where the z-axis distance can be extended to 2m without the loss of transmission factor. Moreover, similar conclusions can be drawn with different implementation methods.

### A. Parameters and Experiments Setting

The numerical analysis of the RB-SLIPT system under NLOS transmission is conducted in MATLAB. To obtain the self-reproducing mode and transmission loss, system parameters, i.e., radius \( r_c \), focal length \( f \), and the interval between lens and mirror \( l \) (\( l = f^2/6 + f \) referring to [25] and [35]) of cat’s eye and gain medium radius \( r_g \), and FFT parameters, i.e., window expand factors \( w \) and sampling number \( N_s \) would influence results. Thus, we choose \( \{ w = 2, N_s = 8192 \} \) as \( \{ r_c = r_g = 1 \text{mm}, f = 5 \text{mm} \} \), and \( \{ w = 2, N_s = 16384 \} \) as \( \{ r_c = r_g = 2 \text{mm}, f = 10 \text{mm} \} \), which satisfy the FFT calculation requirements and show NLOS MTC analysis with a receiver at different spatial positions and altitude angles. Besides, the Fox-Li iteration stops as the difference of the beam field distributions between two iterations is below \( 10^{-3} \). For evaluating NLOS transmission performance, we conduct experiments presenting impacts of the characteristics of reflector M3, i.e., reflectivity \( \bar{R}_3 \) and placement height \( h \). Finally, we perform experiments with different SHG thicknesses and PV equivalent circuit model parameters, which are fitted values from measurements on a real laser PV product [41], [43] for depicting SLIPT performances under NLOS transmission. Moreover, we neglect the transmission loss as the beam passes through lenses or gain medium within MTC. The parameters for SLIPT performance analysis are detailed in Table I.

### TABLE I

| Parameter of RB-SLIPT System [41], [42] | Symbol | Value | Symbol | Value |
|----------------------------------------|--------|-------|--------|-------|
| Window expand factor \( w \)            | \( w \) | 2     | \( N_s \) | 16384 |
| Sampling number \( N_s \)               | \( N_s \) | 16384 | Reverse saturation current \( I_0 \) | \( 9.80 \times 10^{-9} \) A |
| PV conversion responsivity \( \rho_{PV} \) | \( \rho_{PV} \) | 0.0161 A/W | Diode ideality factor \( n \) | 1.105 |
| Number of serial PV cells \( N_{p} \)   | \( N_{p} \) | 40    | Series resistance \( R_s \) | 0.93Ω |
| Shunt resistance \( R_m \)              | \( R_m \) | 52.6kΩ | PV load resistor \( R_{PL} \) | 100Ω |
| Temperature in Kelvin \( T \)           | \( T \) | 298.15K | PD conversion responsivity \( \rho_{PD} \) | 0.4A/A/W |
| APD load resistor \( R_{APD} \)        | \( R_{APD} \) | 10KΩ [39] |       |       |

Fig. 9. Transmission factor \( \gamma \) and computational time for calculating one round-trip transmission as a function of tilted angle \( \varphi \) under various optical element sizes and z-axis transmission distances \( z_s \).

\[ \begin{array}{ll}
\text{(a)} & r_c = r_g = 1 \text{mm}, \ s_z = 1 \text{m} \\
\text{(b)} & r_c = r_g = 2 \text{mm}, \ s_z = 1 \text{m} \\
\text{(c)} & r_c = r_g = 2 \text{mm}, \ s_z = 2 \text{m}
\end{array} \]
C. Output Beam Power Under NLOS Transmission

As in Fig. 10 (a), we also conduct experiments with an off-axis receiver, which is significant for choosing the placements of M3. As the translation angle $\theta$ corresponding to off-axis distance $s_z$ increases, the transmission factors decrease under z-axis moving distances 1m and 2m. Moreover, $\gamma$ remains unchanged as the $\theta$ is below 4°. As the number of sliding computational windows is determined by the z-axis distance, computational time under $s_z = 1m$ is significantly less than under $s_z = 2m$ with the number of sliding computational windows being 34 and 67, respectively. Meanwhile, with the computational design of sliding windows, the required sampling number dropped by a factor of $34^2$ and $67^2$ under 1m and 2m transmission, respectively.

Then, Figs. 10 (b) and (c) plot $P_{out}$ used for SLIPT as a function of various receiver tilted angles $\varphi$ and z-axis distance $s_z$, under both LOS transmission and NLOS transmission as M3 is placed at different distances $h$ away from the LOS link. It can be concluded that under both $s_z = 1m$ and $s_z = 2m$, NLOS links lead to performance reduction, including output power and receiver’s allowable tilted angles decrease, and more input power $P_{in}$ is needed with larger $h$.

D. SLIPT Performance Under NLOS Propagation

Finally, we evaluate the SLIPT Performance of RB-SLIPT under NLOS Propagation with an arbitrarily placed receiver. Figure 11 depicts impacts of input power $P_{in}$, reflectivity $R_3$ of M3, and SHG thickness $l_s$ on received power for both communication $P_{out,IT}$ and wireless power transfer $P_{out,PT}$, under various z-axis distances $s_z$ and M3 placements $h$ with $r_c = r_g = 2mm$.

Experiments have been conducted under different M3 placements and z-axis distances. In Fig. 11 (a), the growth of $P_{in}$ will increase the power used for SLIPT, and the threshold power of RB-SLIPT increases as $h$ and $s_z$ increase. Obviously, larger $R_3$ will bring SLIPT performance improvement as in Fig. 11 (b). SHG thickness $l_s$ reflects the power tradeoff for information and power transfer. As $l_s$ grows, $P_{out,IT}$ increases while $P_{out,PT}$ decreases under various $h$ and $s_z$.

Then, we plot the achievable rate $R_b$ and wireless charging power $P_{chg}$ of RB-SLIPT under NLOS propagation vs. SHG thickness $l_s$ with a non-tilted receiver.

Fig. 12. Achievable rate $R_b$ and charging power $P_{chg}$ of RB-SLIPT under NLOS transmission as a function of $l_s$ with non-tilted receiver.
different receiver’s tilted angles for further illustration as in Figs. 12 and 13. Given the input power $P_{\text{in}} = 100W$ and under $\varphi = 0^\circ$ and $\varphi = 3^\circ$, $P_{\text{chg}}$ decreases while $R_b$ increases with growth of $l_s$. Moreover, the growth rate of $R_b$ slows down as $l_s$ exceeds 0.2mm. As the receiver is tilted, SLIPT performance reduces, especially with larger $h$ and $s_z$. Moreover, we present $R_b$ and $P_{\text{chg}}$ as a function of $\varphi$ under LOS and NLOS transmission. Under LOS transmission with $s_z = 1\text{m}$ in Fig. 14, $R_b$ remains at around 12bit/s/Hz and $P_{\text{chg}}$ is around 4W with the allowable receiver’s tilted angle over $\pm 6^\circ$. Under NLOS transmission with $h = 50\text{mm}, R_b$ and $P_{\text{chg}}$ show no obvious drop with a reduced allowable receiver’s tilted angle. Similar experiments are conducted under $s_z = 2\text{m}$ as in Fig. 15. Larger $P_{\text{in}}$ is required while the allowable receiver’s tilted angle further decreases under NLOS transmission. Still, over 3W charging power and 10bit/s/Hz achievable rate is realized simultaneously within $\pm 4^\circ$ tilted angle, and $P_{\text{in}}$ can be adaptively changed in various NLOS scenarios.

E. Discussion

Numerical results demonstrate that RB-SLIPT can realize 3W charging power and 10bit/s/Hz achievable rate under NLOS propagation. To further improve the RB-SLIPT’s degree of freedom in NLOS scenarios, structures of the cat’s eye in both transceivers and M3 can be designed specifically. Moreover, although this work presents exemplary system designs for illustrating NLOS MTC performance of RB-SLIPT, the deployment of IRS in RB-SLIPT is still worthy of in-depth study. Research on IRS materials and design has recently emerged, with powerful electromagnetic and information control capabilities for high-quality SLIPT [44], [45]. With the implementation and promotion of optical IRSs, optimized energy transfer efficiency, data rate, and large-coverage wireless services can be achieved in RB-SLIPT. Similar open issues also involve speeding up the Fox-Li process, other numerical schemes for obtaining self-reproducing mode with higher accuracy, and deriving analytical expressions of transmission loss in RB-SLIPT for further time saving of MTC analysis.

VI. CONCLUSION

In this paper, we proposed analytical models and simulation tools for MTC analysis of RB-SLIPT with a receiver in an arbitrary position and an arbitrary attitude angle under NLOS propagation. We focused on the beam field propagation analysis with a tilted RB-SLIPT receiver and presented three numerical methods (i.e., NUFFT-based, cubic interpolation-based, and linear interpolation-based) to implement the simulation. The transmission loss and accurate beam field profile can then be obtained for RB-SLIPT in NLOS scenarios. Next, we detailed the implementation of long-distance transmission with an off-axis RBS receiver by proposing a sliding computational window design, which can deal with the contradiction between long-range off-axis transmission and practically tolerable memory cost. After presenting the SLIPT design, we also analyzed the energy/data transfer performance of RB-SLIPT in NLOS scenarios, which demonstrates 3W charging power and 10bit/s/Hz data rate over 2m distance.

APPENDIX

We detailed mapping from $A_\phi(f_x, f_y)$ to $A'_\phi(f'_x, f'_y)$ here for convenience. The beam field on the reference plane can be regarded as a superimposition of infinite plane waves. For each $(f_x, f_y)$, $A_\phi(f_x, f_y)$ denotes the complex amplitude of
one plane wave, of which the wave vector is represented as
\[
k = 2\pi \left[ f_x f_y \right] w(f_x, f_y) \]
\[
w(f_x, f_y) = \sqrt{\lambda^2 - f_x^2 - f_y^2}.
\tag{27}
\]
Similarly, wave vector on the tilted plane can be depicted as
\[
k' = 2\pi \left[ f'_x f'_y \right] w'(f'_x, f'_y) \]
\[
T = \begin{pmatrix} \cos \varphi & 0 & \sin \varphi \\ 0 & 1 & 0 \\ -\sin \varphi & 0 & \cos \varphi \end{pmatrix}
\tag{30}
\]
Next, we get the relation between two coordinate systems as
\[
f_x = \alpha(f'_x, f'_y) = \cos \varphi f'_x + \sin \varphi f'_y + \sin \varphi f'_x - \cos \varphi f'_y
\]
\[
f_y = \beta(f'_x, f'_y) = 0 \times f'_x + 1 \times f'_y + 0 \times w'(f'_x, f'_y)
\tag{31}
\]
Finally, the relation between \(A_d(f_x, f_y)\) and \(A'_d(f'_x, f'_y)\) is
\[
A'_d(f'_x, f'_y) = A_d(\alpha(f'_x, f'_y), \beta(f'_x, f'_y))
\]
\[
= A_d(\cos \varphi f'_x + \sin \varphi w'(f'_x, f'_y), f'_y)
\tag{32}
\]

\section*{References}

[1] K. David and H. Berndt, “6G vision and requirements: Is there any need for beyond 5G?” IEEE Veh. Technol. Mag., vol. 13, no. 3, pp. 72–80, Sep. 2018.

[2] M. Zhang, J. Huang, and R. Zhang, “Wireless power transfer with information asymmetry: A public goods perspective,” IEEE Trans. Mobile Comput., vol. 20, no. 1, pp. 276–291, Jan. 2021.

[3] P. D. Diamantoulakis, G. K. Karagiannidis, and Z. Ding, “Simultaneous lightweight information and power transfer (SLIPT),” IEEE Trans. Green Commun. Netw., vol. 2, no. 3, pp. 764–773, Sep. 2018.

[4] A. M. Abdelhalim, O. Amin, B. Shihada, and M. Alouini, “Spectral efficiency and energy harvesting in mult-cell SLIPT systems,” IEEE Trans. Wireless Commun., vol. 19, no. 5, pp. 3304–3318, May 2020.

[5] J. Fakidis, S. Videv, H. Helmers, and H. Haas, “0.5-Gb/s OFDM-based laser data and power transfer using a GaAs photovoltaic cell,” IEEE Photon. Technol. Lett., vol. 30, no. 9, pp. 841–844, May 1, 2018.

[6] M. Liu et al., “Simultaneous mobile information and power transfer by resonant beam,” IEEE Trans. Signal Process., vol. 69, pp. 2766–2778, 2021.

[7] M. Liu, M. Xiong, Q. Liu, S. Zhou, and H. Deng, “Mobility-enhanced simultaneous lightweight information and power transfer,” IEEE Trans. Wireless Comm., vol. 20, no. 10, pp. 6927–6939, Oct. 2021.

[8] J. Lim, T. S. Khwaja, and J. Ha, “Wireless optical power transfer system by spatial wavelength division and distributed laser cavity resonance,” Opt. Exp., vol. 27, no. 12, p. A924, Jun. 2019.

[9] M. Xiong, Q. Liu, S. Zhou, S. Han, and M. Liu, “Performance of a high power and capacity mobile SLIPT scheme,” IEEE Trans. Commun., vol. 70, no. 7, pp. 4717–4730, Jul. 2022.

[10] M. Xiong, Q. Liu, X. Wang, S. Zhou, B. Zhou, and Z. Bu, “Mobile optical communications using second harmonic of intra-cavity laser,” IEEE Trans. Wireless Commun., vol. 21, no. 5, pp. 3222–3231, May 2022.

[11] K. Matsuhashi, H. Schimmel, and F. Wyrowski, “Fast calculation method for optical diffraction on tilted planes by use of the angular spectrum of plane waves,” J. Opt. Soc. Amer. A, Opt. Image Sci., vol. 20, no. 9, pp. 1755–1762, Sep. 2003.

[12] D. Asoubar, M. Kuhn, and F. Wyrowski, “Acceleration of dominant transversal laser resonator eigenmode calculation by vector extrapolation methods,” IEEE J. Quantum Electron., vol. 51, no. 11, pp. 1–10, Nov. 2015.

[13] M. Shen, S. Wang, L. Hu, and D. Zhao, “Mode properties produced by a corner-cube cavity,” Appl. Opt., vol. 43, no. 20, pp. 4091–4094, Apr. 2004.

[14] F. Shen and A. Wang, “Fast-Fourier-transform based numerical integration method for the Rayleigh–Sommerfeld diffraction formula,” Appl. Opt., vol. 45, no. 6, pp. 1102–1110, Feb. 2006.

[15] A. G. Fox and T. Li, “Resonant modes in a laser interferometer,” Bell Syst. Tech. J., vol. 40, no. 2, pp. 453–488, Mar. 1961.

[16] Y. Xiao et al., “Nonuniform fast Fourier transform method for numerical diffraction simulation on tilted planes,” J. Opt. Soc. Amer. A, Opt. Image Sci., vol. 33, no. 10, pp. 2027–2033, Oct. 2016.

[17] C. Chang et al., “Scaled diffraction calculation between tilted planes using nonuniform fast Fourier transform,” Opt. Exp., vol. 22, no. 14, pp. 17331–17340, Jul. 2014.

[18] Q. Liu, M. Xiong, M. Liu, Q. Jiang, W. Fang, and Y. Bai, “Charging a smartphone over the air: The resonant beam charging method,” IEEE Internet Things J., vol. 9, no. 15, pp. 13876–13885, Aug. 2022.
[36] N. Hodgson and H. Weber, *Laser Resonators and Beam Propagation: Fundamentals, Advanced Concepts, Applications* (Springer Series in Optical Sciences), vol. 108. Berlin, Germany: Springer 2005.

[37] M. Xiong, Q. Liu, and S. Zhou, “Optimization of a mobile optical SWIPT system with asymmetric spatially separated laser resonator,” *IEEE Trans. Wireless Commun.*, vol. 21, no. 11, pp. 9056–9067, Nov. 2022.

[38] A. Lapidoth, S. M. Moser, and M. A. Wigger, “On the capacity of free-space optical intensity channels,” *IEEE Trans. Inf. Theory*, vol. 55, no. 10, pp. 4449–4461, Oct. 2009.

[39] F. Xu, M. Khalighi, and S. Bourennane, “Impact of different noise sources on the performance of pin- and APD-based FSO receivers,” in *Proc. 11th Int. Conf. Telecommun.*, Graz, Austria, Jun. 2011, pp. 211–218.

[40] D. Chenvidhya, K. Kirtikara, and C. Jivacate, “On dynamic and static I–V characteristics of solar cell modules having low and high fill factors,” in *Proc. 3rd World Conf. Photovoltaic Energy Convers.*, Osaka, Japan, May 2003, pp. 1927–1929.

[41] MHHoPower. *Photovoltaic Converter YCH-H6424 Datasheet*. Accessed: Dec. 10, 2022. [Online]. Available: http://www.mhgopower.com/images/YCH-H6424_15V_PPC_Datasheet_Rev_2.3_03-12-2020.pdf

[42] B. R. Strickland, M. J. Lavan, E. Woodbridge, and V. Chan, “Effects of fog on the bit-error rate of a free-space laser communication system,” *Appl. Opt.*, vol. 38, no. 3, pp. 424–431, Jan. 1999.

[43] M. Perales et al., “Characterization of high performance silicon-based VMJ PV cells for laser power transmission applications,” *Proc. SPIE*, vol. 9733, pp. 166–182, Mar. 2016.

[44] J. C. Liang et al., “An optically transparent reconfigurable intelligent surface with low angular sensitivity,” *Adv. Opt. Mater.*, Nov. 2022, Art. no. 2202081.

[45] J. Tao et al., “Mass-manufactured beam-steering metasurfaces for high-speed full-duplex optical wireless-broadcasting communications,” *Adv. Mater.*, vol. 34, no. 6, Feb. 2022, Art. no. 2106080.

**Mingliang Xiong** received the B.Eng. degree in communications engineering from the Nanjing University of Posts and Telecommunications, Nanjing, China, in 2017. He is currently pursuing the Ph.D. degree with the College of Electronics and Information Engineering, Tongji University, Shanghai, China. He was awarded the National Scholarship in 2020, the Huawei Scholarship in 2021, and the Phoenix Contact Scholarship in 2018. His research interests include optical wireless communications, wireless power transfer, and the Internet of Things.

**Mengyuan Xu** received the B.E. degree in computer science and technology from the Jiangsu University of Science and Technology, Zhenjiang, China, in 2019. She is currently pursuing the Ph.D. degree with the College of Electronics and Information Engineering, Tongji University, Shanghai, China. Her research interests include the development of remote wireless charging technology, wireless communications, and the Internet of Things.

**Shuaifan Xia** received the B.S. degree in information security from Hangzhou Dianzi University, Zhejiang, China, in 2022. He is currently pursuing the M.S. degree with the College of Electronics and Information Engineering, Tongji University, Shanghai, China. His research interests include optical wireless power transfer and communication, and the Internet of Things.

**Mingqing Liu** (Graduate Student Member, IEEE) received the B.S. degree in computer science and technology from Northwest A&F University, Yangling, China, in 2018. She is currently pursuing the Ph.D. degree with the College of Electronics and Information Engineering, Tongji University, Shanghai, China. Her research interests include wireless power transfer, simultaneous lightweight information and power transfer, integrated communication and positioning, and the Internet of Things.

**Hao Deng** (Member, IEEE) received the B.S. and Ph.D. degrees from the Department of Physical Electronics, University of Electronic Science and Technology, Chengdu, China, in 2007 and 2015, respectively. He is currently an Assistant Professor with the School of Software Engineering, Tongji University, Shanghai, China. His research interests include remote wireless charging technology, wireless communications, and the Internet of Things.

**Qingwen Liu** (Senior Member, IEEE) received the B.S. degree in electrical engineering and information science from the University of Science and Technology of China, Hefei, in 2001, and the M.S. and Ph.D. degrees from the Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, in 2003 and 2006, respectively. He is currently a Professor with the College of Electronics and Information Engineering, Tongji University, Shanghai, China. His research interests include wireless power transfer and the Internet of Things.

**Mingyuan Xu** received the B.E. degree in computer science and technology from the Jiangsu University of Science and Technology, Zhenjiang, China, in 2019. She is currently pursuing the Ph.D. degree with the College of Electronics and Information Engineering, Tongji University, Shanghai, China. Her research interests include the development of remote wireless charging technology, wireless communications, and the Internet of Things.