Experimental Realization of Near-Field Photonic Routing with All-Electric Metasources

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(Dated: April 14, 2020)

The spatially confined evanescent microwave photonics have been proved to be highly desirable in broad practical scenarios ranging from robust information communications to efficient quantum interactions. However, the feasible applications of these photonics modes are limited due to the lack of fundamental understandings and feasible directional coupling approaches at sub-wavelengths. Here, we experimentally demonstrate the efficient near-field photonic routing achieved in waveguides composed of two kinds of single-negative metamaterials. Without mimicking the polarization features, we propose all-electric near-field metasource in subwavelength scale and exemplify its near-field functions like Janus, Huygens and spin sources, corresponding to time-reversal, parity-time and parity symmetries of its inner degree of freedom. Our work furthers the understandings about optical near-field symmetry and feasible engineering approaches of directional couplings, which would pave the way for promising integrated microwave photonics devices.

Microwave photonics have been attached a lot of attentions for its applications from classical regions to quantum aspects [1–5]. The microwave photonics have the millimeter wavelength for flexible on-chip photonics devices [1] and the same energy order for artificial atom physics in superconducting circuits [4, 5] or spin cavities [6, 7]. As result, microwave photonics have become one of the important bridges for communicating information and transferring energy, from the macroscopic signal process devices [1, 8] to the quantum interactions between two artificial atoms [5]. The miniaturized on-chip microwave photonics requires the efficient routing and ultrafast switching for microwave inputs in the deep subwavelength scale [1, 9]. This is an open challenge due to the lack of understandings about the symmetry and geometry of near-field microwave photonics.

So far, this subwavelength near-field routing is usually achieved by using the local polarizations of light: electric field $E$ and magnetic field $H$. One well-established way is exploiting the spin-orbit coupling and quantum spin Hall effect (QSHE) states of light [10–14]. The particle scatterings of the incident chiral light [10] or the local chiral electric dipoles [15] will excite the directional surface wave due to the non-zero transverse spin ($\propto \text{Im}(E^{*} \times E + H^{*} \times H)$) and spin-momentum locking [10, 16], similar counterparts of which can be found universally in other wave systems, such as acoustic [17] and elastic waves [18]. The other way is based on the relative phase delay combinations of electric and magnetic fields [19–21]. The super-positions of geometrically orthogonal electric and magnetic dipoles can excite the surface waves associated with Poynting vectors ($\propto \text{Re}(E^{*} \times H)$) and reactive power ($\propto \text{Im}(E^{*} \times H)$) respectively, which result in different behaviours beyond spin-momentum locking [19–21]. These approaches provide good understandings about the near-field photonics routing. It implies that the symmetry of near-field excitations would be associated with that of sources. The question will be whether we can achieve the photonics routing from a deep perspective, such as the symmetry features of near-field photonic systems.

In this Letter, we demonstrate that the efficient near-field microwave photonics routing based on the structured all-electric metasource in the subwavelength scale. The metasource is composed of only the phase-delayed electric source elements, such as voltage ports or electric dipoles, which will be placed in the subwavelength area. It is known that the magnetic dipole with strong strength (c factor [19] compared with electric dipole) is usually hard to achieve practically due to weak interactions between almost optical media and magnetic fields, and design complexities in broadband magnetic metamaterials. Different from the schemes based on the polarization profiles [10, 15, 19–21], the physical mechanism underlying our method is the symmetry transformation invariance between the environments and the inner degree of freedom in metasources. In our work, three kinds of symmetries: parity ($\hat{P}: r \rightarrow -r$), time-reversal ($\hat{T}: t \rightarrow -t$) and parity-time ($\hat{PT}: r \rightarrow -r, t \rightarrow -t$) symmetry, have been discussed. We found that the metasource can reproduce effective Janus source under $\hat{T}$-symmetry, Huygens source under $\hat{PT}$-symmetry and spin source under $\hat{P}$-symmetry. We experimentally verify these predicted phenomena based on the 2D microwave photonic system experimentally.

The surface evanescent wave can possess some special dynamic properties, such as supermomentum [23, 24], chiral polarized field and transverse spin, as shown in Fig. 1(a). They are the core essences for the polarization-based schemes [10, 15, 19–21]. Here, we consider one interesting QSHE state that happens on the interface between two different metamaterials [22]: epsilon-negative (ENG) and mu-negative (MNG), which correspond to two types of topological origins and could be described by the complex Chern number for optical helicity [25]. For simplicity, we focus on the transverse magnetic (TM) QSHE mode. As shown in Fig. 1(b), we consider the surface wave mode $\psi$ is supported by the photonics system $\mathcal{H}$ and excited by the harmonic oscillated source term $\psi_s$ with the frequency $\omega$, which can be represented as the Schrödinger
equation like form:
\[ \omega \psi = \mathcal{H} \psi + \psi_s. \] (1)

Its symmetry analysis will be: (1) If we apply the parity transformation \( \hat{P} \), the equation will be:
\[ \omega \hat{P} \psi \hat{P}^{-1} = \hat{P} \mathcal{H} \hat{P}^{-1} \hat{P} \psi \hat{P}^{-1} + \hat{P} \psi_s \hat{P}^{-1}, \] (2)

which reflects a fact that: if the \( \psi_s = \hat{P} \psi_s \hat{P}^{-1} \), the source will excite the \( \psi \) in the system \( \mathcal{H} \) and \( \hat{P} \psi \hat{P}^{-1} \) in the system \( \hat{P} \mathcal{H} \hat{P}^{-1} \) simultaneously; (2) If we apply the time-reversal transformation \( \hat{T} \):
\[ \omega \hat{T} \psi \hat{T}^{-1} = \mathcal{H} \hat{T} \hat{P} \hat{T}^{-1} \hat{T} \psi \hat{T}^{-1} + \hat{T} \psi_s \hat{T}^{-1} \] (3)

which reflects a fact that: if the \( \psi_s = \hat{T} \psi \hat{T}^{-1} \), the source will excite the \( \psi \) in the system \( \mathcal{H} \) and \( \hat{P} \psi \hat{P}^{-1} \) in the system \( \mathcal{T} \hat{H} \hat{T}^{-1} \) simultaneously; (3) If we apply the parity-time transformation \( \hat{P} \hat{T} \):
\[ \omega \hat{P} \hat{T} \psi \hat{P} \hat{T}^{-1} = \hat{P} \mathcal{H} \hat{P} \hat{T}^{-1} \hat{P} \hat{T} \psi \hat{P} \hat{T}^{-1} \]
\[ + \hat{P} \hat{T} \psi_s \hat{P} \hat{T}^{-1} \] (4)

which reflects a fact that: if the \( \psi_s = \hat{P} \hat{T} \psi_s \hat{P} \hat{T}^{-1} \), the source will excite the \( \psi \) in the system \( \mathcal{H} \) and \( \hat{P} \psi \hat{P}^{-1} \) in the system \( \hat{P} \mathcal{H} \hat{P}^{-1} \) simultaneously. These analysis is the core point of this work: the directional routing can be realized by the symmetry properties of \( \mathcal{H} \) but without considering the polarization details in \( \psi \). Taking these facts together, we can construct such a system in Fig. 1(c) and there will exist four modes \( \{ \psi_i \} (i = 1...4) \) corresponding to the four systems \( \mathcal{H}, \mathcal{T} \mathcal{H} \mathcal{T}^{-1}, \mathcal{P} \mathcal{H} \mathcal{P}^{-1}, \mathcal{P} \mathcal{T} \mathcal{H} \mathcal{T} \mathcal{P}^{-1}. \) It’s obvious that

![FIG. 1. The near-field photonic routing of all-electric metasources based on symmetry analysis. a, the dynamic properties of the evanescent photonic mode. b, the photons planar waveguide system \( \mathcal{H} \) composed of the epsilon-negative (ENG, namely \( \varepsilon < 0 \) and \( \mu > 0 \)) and mu-negative (MNG, namely \( \varepsilon > 0 \) and \( \mu < 0 \)) meta-material can support the non-trivial QSH state. c, the combined system that contains the four different symmetry parts with respect to the source. e, the metasource is composed of electric sources and its geometrical scale is smaller than the working wavelength, namely in deep subwavelength. f, the demonstrations of near-field routing behaviours of metasources with different symmetries. The normalized \( |H_x| \) fields are plotted. The height of central MNG is 30 cm, the working frequency is 2.7 GHz. \( d = 1 \text{ mm} \) \( (d \ll \lambda) \), \( \varepsilon = -9.44, \mu = 1.00 \) for ENG, \( \varepsilon = 6.58, \mu = -0.35 \) for MNG. [22]](image)

![FIG. 2. Magnetic field amplitude angular spectra of metasources in a homogeneous medium as a function of \( \tau, k \) and spin \( s_z \) in the \( xOy \) plane. a, \( \mathcal{T} \) symmetry metasource (Janus source). b, \( \mathcal{PT} \) symmetry metasource (Huygens source). c, \( \mathcal{P} \) symmetry metasource (Spin source). Here, \( \mathcal{H}_0^A = \frac{\omega k_0}{\pi c} \) and \( s_0 \) is the spin angular momentum when \( k = \tau, s_0 = s_0 e_z \).](image)
M dipole, not relying on the field polarization. Evaluations shown in Fig. 1(f), we can see that the same near-cites the mode pairs {\(M_i\)} current generator [26]. Considering the harmonic oscillation magnetic spectrum descriptions about their near-field behaviour. The ENG/MNG waveguides.

Besides the symmetry analysis, we will give the theoretical details in Fig. 1(f) based on Eq. 7. For \(\hat{T}\)-symmetry metasource(Janus source), there are three voltage sources: \(\mathcal{M} = 1V\) at the center position (0,0), \(\mathcal{M} = +1V\) at the position (0, d) and \(\mathcal{M} = -1V\) at the position (0, -d). The evanescent photonics modes can be represented with the complex wave vector \(\hat{\mathbf{k}} = (\hat{k}, \hat{\tau}, 0)\). The angular spectrum for \(\hat{T}\)-symmetry will be:

\[
\mathcal{H}_T^A(k, \tau) = \frac{\omega}{8\pi^2} k_0^2 \sqrt{\frac{1}{c}} \left(1 + e^{-\tau d} + e^{\tau d}\right) e_s.
\]

When \(\tau d \ll 1\), \(\mathcal{H}_T^A \propto |1 + 2\tau d|\), which reflects that the \(\hat{T}\)-symmetry meta-source will be strongly associated with the decay rate \(\tau\), as shown in Fig. 2(a). In the same process, the \(\hat{T}\)-symmetry metasource (Huygens source), it will be:

\[
\mathcal{H}_{\hat{T}}^A(k, \tau) = \frac{\omega}{8\pi^2} k_0^2 \sqrt{\frac{1}{c}} \left(1 + i e^{-i k d} + i e^{i k d}\right) e_s.
\]

and \(\mathcal{H}_{\hat{T}}^A \propto |1 + 2k d|\) when \(k d \ll 1\), which shows that the \(\hat{P}\)-symmetry will result in the k-dependent coupling strength, as shown in Fig. 2(b). For \(\hat{P}\)-symmetry metasource(spine source), it will be:

\[
\mathcal{H}_P^A(k, \tau) = \frac{\omega}{8\pi^2} k_0^2 \sqrt{\frac{1}{c}} \left(e^{-\tau d} - e^{\tau d} + i e^{-i k d} + i e^{i k d}\right) e_s.
\]
and $|\vec{H}_p^d| \propto 2d|\tau \pm k|$ when $d \ll \lambda$, which reflects that the meta-source with $\hat{P}$-symmetry will be strongly locked with the spin angular momentum $s_z \propto \tau k$, as shown in Fig. 2(c). In the following, we will verify the near-field behaviour of meta-source experimentally.

In microwave photonics regime, the two-dimensional (2D) transmission lines (TLs) loaded with lumped circuit elements will be a convenient and simple platform to realize arbitrary effective $\varepsilon$ and $\mu$ and observe optical wave propagations. Until now, many high-performance metamaterials have been constructed to achieve the required optical responses in this platform and enable extensive applications, such as cloaking [30], hyperbolic dispersion [31] and topological photonics [22, 32]. Here, we design a TL system in Fig. 3(a), which achieve the equivalent photonic system in Fig. 1(c). The effective parameters can be derived according to the TLs effective medium theory, which have been calculated in Fig. 3(b). We can see that the TL metamaterials will support TM modes in the frequency range $2.3 \sim 3.0$ GHz as Fig. 3(c). As shown in Fig. 3(d), the voltage port arrays with spatial distributed amplitude and phase have been used to induce effective near-field sources. The simulated and experimental results of these sources are shown in Fig. 4. The effective Janus source will excite the mode pairs with $\hat{T}$-symmetry, the Huygens source will induce the branches with $\hat{PT}$-symmetry and the spin source will stimulate the branches with $\hat{P}$-symmetry. The experimental results are in good agreement with the theoretical analysis and numerical simulations. (More details in Supplementary)

Finally, we discuss the physical reason for the same behaviour between our symmetry-based scheme and the polarization proposals in the previous studies [10, 15, 19, 20]. The main reason is that we share the same symmetry features as the near field physical quantities: Poynting vector $\mathcal{J}$, reactive power $\mathcal{R}$ and spin density $s$. One can find that: $\mathcal{J}$ satisfies $PT$-symmetry ($PT\mathcal{J}(PT)^{-1} = \mathcal{J}$), $\mathcal{R}$ satisfies $\hat{T}$-symmetry ($\hat{T}\mathcal{R}\hat{T}^{-1} = \mathcal{R}$) and $s$ satisfies $\hat{P}$-symmetry ($\hat{P}s\hat{P}^{-1} = s$). The original Janus, Huygens and spin sources are strictly associated with these physical quantities and thus will inherit these symmetry properties naturally. Our scheme removed the requirement of magnetic dipoles and become experimentally tractable. For example, in the optical regime, the meta-source can be realized by the nano-particle arrays or other scatters in the subwavelength scale.

To summarize, we have proposed the subwavelength all-electric meta-sources for the near-field microwave photonics routing based on parity, time-reversal, parity-time symmetry. According to these symmetry features, we have exemplified and observed the fertile functions of excitations supported on MNG/ENG interface based on photonic microwave TL system, corresponding to the Janus, Huygens and spin sources. We have shown alternative approach to design the near-field photonics sources in additions to the polarization engineering, which reflects the inner symmetry properties of the near-field systems. Our work would improve the understanding about the geometry and topology in near field and inspire new ideas for controlling photonic evanescent modes, i.e., selective wireless energy transfer [33, 34] and future integrated optical devices [35–37].

This work is supported by the National Key R&D Program of China (Grant No. 2016YFA0301101), by the National Natural Science Foundation of China (NSFC) (Grants No. 11775159, and No. 61621001), by the Natural Science Foundation of Shanghai (Grants No. 18ZR1442800, No. 17ZR1443800, No. 18JC1410900), by China Postdoctoral Science Foundation (Grants No. 2019TQ0232, No. 2019M661605), and by the Opening Project of Shanghai Key Laboratory of Special Artificial Microstructure Materials and Technology.
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