Numerical Investigation of the Performance of OAM-Mode Shifting Recirculating Delay Loop Under the Effect of Mode Shifter Displacement

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Abstract—**We investigate the effect of OAM mode shifter displacement on the performance of the OAM-mode shifting recirculating delay loop by simulating the beam propagation using Kirchhoff-Fresnel diffraction. Simulation results indicate that 20 delayed replicas may be obtained with >10 dB signal-to-crosstalk ratio (SCR) if alignment is perfect and ℓ_{shift}=+1.**

Keywords— Optical Memories, Space Division Multiplexing.

I. INTRODUCTION

Delay lines are essential to enable various signal processing functions such as correlation, filtering, and beamforming[1]. Delaying the signals in the optical domain can help process high-speed signals that are already in the optical domain. Generating the delays using optical recirculating delay loops has gained attention due to providing different delayed replicas of the signal within a compact setup. For example, in a wavelength-shifting recirculating delay loop[2] : (i) a beam splitter sends the signal to enter the loop, (ii) every time the signal recirculates around the loop, it accumulates delay equivalent to the loop propagation delay, (ii) the recirculating signal is wavelength shifted to a different wavelength carrier using a frequency shifter, and (iv) when the signal reaches back the splitter, the splitter sends part of the recirculating signal power to the output while sending the rest to the loop to generate additional delayed and wavelength shifted recirculations. Thus, at the output, different delayed replicas of the signal exist at different wavelength carriers, and all of these replicas can be accessed at the output simultaneously.

Space division multiplexing was recently reported as another useful domain for building recirculating delay loops. For example, in [3], [4], the delay loop shifted every recirculation to a new orbital angular momentum (OAM) mode carrier instead of a new wavelength. Hence, different delayed replicas of the signal that are carried by different OAM modes could be accessed simultaneously at the loop output. We note that the OAM modes form an orthogonal spatial mode bases and that each OAM beam has a helical phase front that is defined by the OAM order (ℓ), where ℓ is the number of 2π phase shifts in the azimuthal direction.

However, the performance of the OAM-mode shifting recirculating delay loop was limited by two factors: (i) inter-modal crosstalk at the loop output, and (ii) loss that happened in the loop due to the multiple passes through the 50:50 beam splitter. The inter-modal crosstalk between the replicas at the loop output could happen because of the: (i) OAM mode shifter displacement inside the loop, (ii) limited modal purity and coupling efficiency in the receiver, or (iii) misalignment between the transmitter and receiver apertures, especially that the loop can double down on this misalignment effect if the loop mirrors were not optimally aligned. Therefore, the demonstrations were so far limited to generating the signal with only three delayed replicas. The authors of [4] provided

an estimate of the maximum number of generatable delayed replicas with signal-to-crosstalk ratio (SCR) above a certain threshold by assuming the crosstalk spectrum has a Lorentzian distribution with the width (γ).

A laudable goal would be to perform a more accurate numerical analysis to estimate the number of generatable replicas with SCR above a certain threshold and investigate the impact of different impairments in the system, such as the mode shifter displacement. One potential method to perform this analysis is using Kirchhoff-Fresnel diffraction (KFD). For example, the authors of [5] reported using KFD numerically to determine the design considerations for building an OAM multiplexed communication link.

In this paper, we numerically investigate the performance of the OAM-mode shifting recirculating delay loop under the effect of OAM mode shifter displacement by numerically simulating the beam propagation inside the loop using KFD. Simulation results indicate that 20 delayed replicas with >10 dB SCR may be accessed if alignment is perfect and ℓ_{shift}=+1. However, 14.6 mm of mode shifter displacement reduces the number of accessible replicas with >10 dB SCR to below 15 depending on the input beam mode order (ℓ_{in}).

II. SIMULATION SETUP

The setup is shown in Fig.1. We first generate a Gaussian beam with the parameters listed in Table. 1. We convert the beam to an OAM beam with the order ℓ_{in} by passing it through a phase plate. The phase plate is loaded with the phase of $exp(j\ell_{in}\varphi)$ where φ is the azimuthal angle. We then send the OAM beam to the loop (blue shaded area in Fig. 1) where: (i) a 50:50 beam splitter directs part of the incoming beam to the recirculating loop while the other part directly exits the loop giving our baseline replica ($n=0$), (ii) four mirrors are used to control the propagation distance and loop delay (T), where we simulate the beam propagation here using KFD, (iii) an OAM mode shifter adds ℓ_{shift} to the OAM mode order of the recirculating beam, and (iv) when the beam reaches back the splitter, the splitter sends part of the power the output, while directing the rest back to the loop to

Table. 1. Simulation parameters

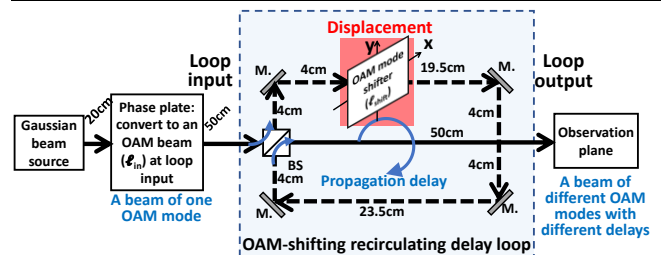| Wavelength	1550 nm	Source beam waist	10 mm
No. of pixels	1024	Size of simulation	5 cm × 5 cm
Loop delay	2.1ns (63 cm)	------	------

Fig. 1. Simulation setup. M.:Mirror, BS: 50:50 Beam splitter.

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generate additional n recirculations. Thus, at the loop output observation plane, a beam with multiplexed OAM modes of $\sum_{k=0}^{n} \ell_{in+k.shift}$ is produced, such that every OAM mode carries a signal replica with an accumulated delay of the amount nT. We perform our simulation analysis by generating the output for each of the n recirculations independently. We also attenuate every recirculation output by $n{\times}3$-dB to include the beam splitter loss. Then, we produce the composite output beam by coherently combining all the output beams.

III. VERIFICATION OF SIMULATION MODEL

To verify our model, we simulate a loop that is perfectly aligned (OAM mode shifter displacement, $d=0$) and generate the baseline output with only two recirculations (i.e., generate the recirculations $n=0,1,2$). We set the loop to have $\ell_{shift}=+1$ and $\ell_{shift}=+2$ and show the loop output results in Fig. 2. In Fig. 2(a-c), we plot the intensity and phase profiles for each output beam, independently. We also plot the OAM spectrum showing that each beam has >60 dB of modal purity. We calculate the OAM spectrum coefficients (C_ℓ) using $|C_\ell|^2=|\iint E_l(x,y).E_2^*(x,y)dxdy|^2$ where $E_l(x,y)$ is the electric field of the received beam, and $E_2^*(x,y)$ is the electric field of a pure $LG_{\ell,0}$. Fig. 2(d) shows the combination at the loop output, where the different OAM modes are still distinct in the spectrum.

Next, we add displacement to the OAM mode shifter of $d=1.4\ mm$ (in the x-direction) and show the output beams in
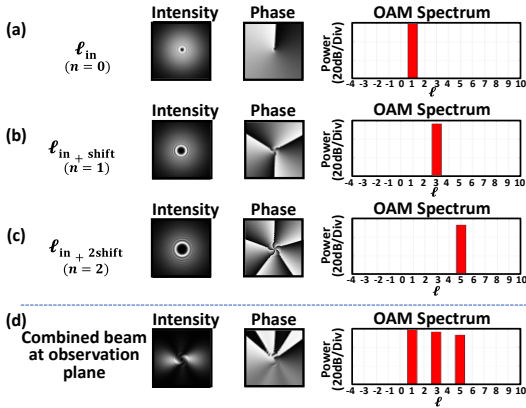

Fig. 2. (a-c) The generated output replicas using the simulator when $d=0$ for $n=0,1,2$. We show the intensity, phase, and OAM spectrum for each output beam. (d) The coherently combined beam at the output plane.
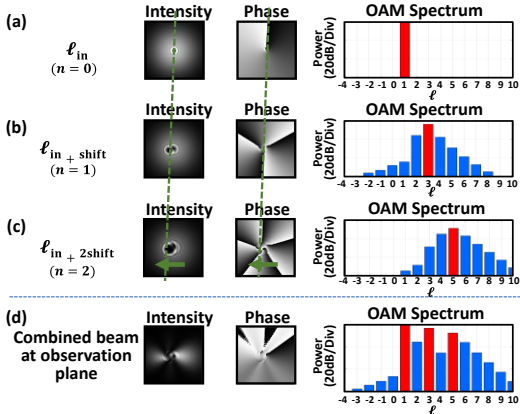

Fig. 3. (a-c) The generated output replicas using the simulator when $d=1.4$ mm for $n=0,1,2$. We show the intensity, phase, and OAM spectrum for each output beam. Here, the recirculations observe worse modal purity causing higher inter-modal crosstalk. (d) The coherently combined beam at the output observation plane.

Fig. 3. The intensity profiles of Fig. 3(a-c) show that the generated beams are not symmetric around the center anymore. Additionally, the OAM spectra show degraded modal purity (i.e., power leakage into the neighboring modes), leading to inter-modal crosstalk when combining the beams. In Fig. 3(d), we show the coherently combined beam at the output and its spectrum.

IV. LOOP PERFORMANCE INVESTIGATION

The loop performance investigation is carried out by measuring the SCR for the replicas at the output and finding the number of replicas with >10-dB of SCR. The SCR is measured using the on-off method:

$$SCR(n) = \frac{P(n, \ell_{in+n.shift})}{\left[\sum_{k=0}^{\max(n)} P(k, \ell_{in+k.shift})\right] - P(n, \ell_{in+n.shift})}$$

Where n is the replica's number under SCR investigation, and we limit n in our investigation to 20 replicas (i.e., $n \in [0,1,2,...,19]$) assuming the system can accommodate 60 dB of splitter loss. $P(n, \ell_{in+n.shift})$ is the power from the nth replica at the OAM mode $\ell_{in+n.shift}$. We show the measured SCRs in Fig. 4 for the cases of $\ell_{in}=0, -15, -30$ (rows) and $\ell_{shift}=+1, +3$ (columns). We also consider the OAM mode shifter displacement scenarios of $d=0, 4.8, 9.6, 14.6, and 19.5$ mm. By analyzing the results of Fig. 4(a-c), we can conclude that 20 recirculations can be accessed when alignment is perfect ($d=0$) and $\ell_{shift}=+1$ with >10-dB SCR. Also, we can notice that $\ell_{in}=-30$ (Fig.4 (c)) provides better results for the displacements of $d=14.6$ or 19.5 mm, producing 15 replicas with >10-dB SCR. By analyzing the results in Fig. 4(d-f) for $\ell_{shift}=+3$, we find that 20 replicas can be accessed with >10-dB SCR only when $d=0$ or 4.8 mm and when $\ell_{in}=-15$, or -30.
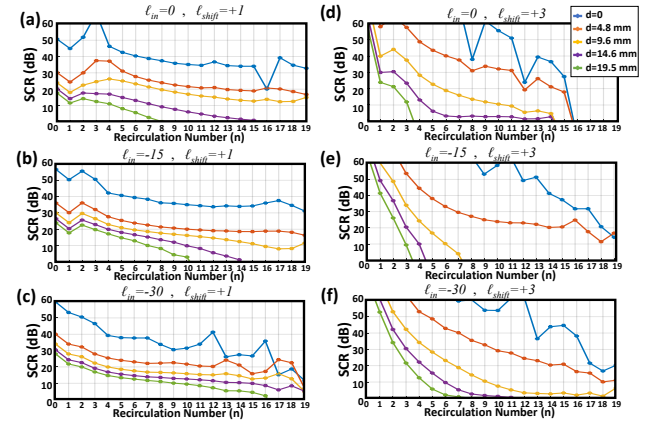

Fig. 4. The measured signal-to-crosstalk ratio (SCR) in simulation for different OAM mode shifter displacement scenarios.

V. REFERENCES

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