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We experimentally demonstrate collective amplified modes along bent chains of directly coupled, amplifying spherical microdroplet resonators. The chains, comprising \(\sim 40\) non-contacting resonators, were bent through angles up to \(\sim 25^\circ\). The modal probability of the system shows a sharp drop upon bending through small angles (\(\sim 10^\circ\)), and thereafter changes minimally under further bending. The frequency response is significantly maintained under bending. We numerically study the transmittance of a chain of non-contacting amplifying resonators using finite-difference-time-domain calculations, and observe that nanojet filamentation influences coupling at the bend. A self-correcting mechanism of propagation is observed, originating from the lensing effect of the spherical resonator. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4826577]

Co-operative phenomena in resonator-based photonic devices are a subject of intense scrutiny.\(^1\) Of the various devices studied, coupled resonator optical waveguides (CROWS) have seen a large research activity in recent years.\(^2\) These structures comprise a series of identical resonators, typically placed in contact to each other, that guide light using modes that couple resonantly across the entire structure. Such devices have been acclaimed for their potential regarding generation of slow or fast light states,\(^13\) all-optical processes using nonlinearity,\(^14\) or higher-order photonic structures such as delay lines.\(^15\) Although such waveguides were primarily envisaged for evanescent coupling using whispering gallery modes (WGM's), experiments have also demonstrated the viability of direct-coupling in the domain of straight chains.\(^7\) In this scenario, the propagation is realized by special longitudinal modes called nanojet-induced modes (NIMs), mediated by optical jets forming at the edge of a microsphere. A prime advantage of such NIM-based modes is that they are more tolerant to size disorder compared to whispering gallery modes, and hence are shown to dominate transport in long straight chains of spherical resonators.\(^5\) Recently, ray analysis of NIM propagation through large spheres has revealed many interesting features in long straight chains, such as periodic focussing, beam profile narrowing, etc.\(^6\)

A desirable feature of such a chain-like device is the possibility of its bending. In this regard, evanescent coupling has been the matter of choice due to the omnidirectional coupling ability of the WGM modes. Significant theoretical and experimental studies of bent arrays and CROW branches have been reported in systems using evanescent coupling.\(^16\)\(^\text{–}\)\(^18\) In comparison, direct-coupled systems exploiting NIM modes are prone to inherent radiative losses; hence, any additional loss due to bending is undesirable. However, one established way of overcoming losses is by incorporating optical gain, creating an “active” system.\(^19\)\(^\text{–}\)\(^23\) Features of gain enhancement have been theoretically analyzed, and experimentally studied in chains of plane-parallel Fabry-Perot resonators.\(^22\) Recently, we have demonstrated collective modes in an amplifying linear array of spherical microdroplet resonators in non-contact mode and showed that these modes were realized by direct-coupling of the Fabry-Perot resonances of a spherical cavity.\(^24\) The radiative losses in the transport were compensated by the optical gain, which established a continuous longitudinal mode in the chain. These collective modes are potential carrier modes in a direct-coupled active CROW. In this paper, we further exploit the optical gain by experimentally demonstrating continuous bending of the chain through small angles. We report on the probability of collective modes and their frequency response as a function of bending angle. We find that few-resonator size mismatch does not seriously compromise the existence of the modes as well as their frequency dependence. We perform two-dimensional finite-difference-time-domain (FDTD) analysis for the transmittance of a linear chain of non-contacting resonators, where we observe filamentation of the NIM modes which influence the coupling at the bends. We further observe a self-correcting behavior in the light propagation realized by the spherical shape of the resonators.

Figure 1 depicts the method of generation of the CROW. A solution of Rhodamine 6G in methanol (2 mM) is stored in the reservoir R and is subjected to pressure by a non-reactive gas, leading to its emission via the aerosol generator V. The generator comprises a 10 \(\mu\)-bore microcapillary, to which a piezo-electric gate is connected. When a periodic square voltage (0–3 V) is applied to the gate, the liquid emits out of the microcapillary in the form of a chain of monodisperse microspherical droplets.\(^25\) These droplets are separated by several micrometers, thus preventing evanescent coupling. Under excitation by a frequency-doubled Nd:YAG laser (\(\lambda = 532.8 \text{nm}\), pulswidth \(\sim 25\) ps, repetition rate 10 Hz), the rhodamine population in the droplets is inverted, creating optical gain. The subsequent emission and amplification of fluorescence lasted for about 10 ns.\(^26\) Over this short time, the droplet chain was effectively static. This enabled us to image the array onto a spectrograph-CCD system (not shown) using lens L1, while L2 imaged it onto an

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imaging CCD. Indeed, the images show the discrete droplets clearly, without any washing out of the droplet images. Next, we achieved bending in this array by utilizing a controlled, directed air flow. To that end, a tapered nozzle N was brought into vicinity of the microdroplet chain and \( N_2 \) gas blown at a mild pressure. By adjusting the pressure and the distance between the nozzle and the chain, we obtained bending up to \( \sim 25^\circ \), without severely distorting the chain. The gas jet led to a minor deshaping in the droplets at the bend, but surface tension quickly induced a spherical shape. Figure 1 shows representative images of bent arrays, with angles \( \theta_{bend} \) varying as \( 0^\circ \) (straight), \( 10^\circ \), \( 14^\circ \), \( 18^\circ \), and \( 24^\circ \), respectively.

The evidence of collective modes is given by the transverse emission captured by a spectograph, which provides spatio-spectrally resolved images of the system, summarized in Figure 2. Fig. 2(a) shows the emission from the straight array. A few vertical bright streaks are observed, each one being the image of the source (here, the linear chain) in the respective wavelength. Thus, these streaks depict the collective carrier mode excited across the entire array. The background shows equispaced broad patches, which depict the whispering gallery modes of the individual microdroplets. These high-quality WGM modes (\( Q > 5000 \)) enabled us to characterize the diameters and size dispersions of the droplets. Accordingly, the average diameter of the droplet was found to be \( 17.3 \mu m \), with a spread of \( \sim 80 \text{nm} \), while they were spaced \( \sim 8 \mu m \) apart. The carrier mode, however, is the hybrid mode manifested by the direct coupling of the various spherical Fabry-Perot resonators. The threshold energy for these modes was measured to be \( \sim 1 \mu J \). Figs. 2(b) and 2(c) show the carrier mode excitation when the chain is bent by \( 18^\circ \) and \( 24^\circ \), respectively. In the region of the bend, the droplets of the array are relatively displaced with respect to the axis of the initial straight array. Accordingly, the images of the bent array in the respective wavelength appear as bent curves. Clearly, multiple carrier modes are excited despite the bend, proving that the optical gain could overcome the bending losses. A few chosen modes have been magnified on the right. We observe that the intensity distribution in the arrays is not uniform along the chain but highly heterogeneous. Some intense hot-spots are seen along the array at random positions. Importantly, the polydispersity causes the whispering gallery modes to wash away, as seen from the image background. But, since the NIM modes are resilient to disorder, they still exist in the system.

We measured the frequency distribution of carrier modes over one hundred spectra at a given bending angle. This also enabled us to measure the dependence of the carrier mode buildup on the bending angle, quantified as the probability of modes at the bending angle. Figure 3 depicts the modal density, the number of modes in the observed interval, as a function of \( \theta_{bend} \). Evidently, the number rapidly decays to about 30% within the first few degrees of bending (\( \sim 10^\circ \)). Thereafter, the density did not vary significantly with increasing bending. Figure 3(inset) shows the frequency distribution of the carrier modes. The straight array produces modes in well-defined frequency intervals. These intervals are separated with the Fabry-Perot free spectral spacing of single individual microresonators. In the context of CROWs, these histograms are reminiscent of Fabry-Perot signatures observed by Yang and Astratov in NIM’s in linear chains of touching microspheres, with the difference that the spectral spacing corresponded to an effective cavity length of two microspheres. With the introduction of bends, the two intervals start to merge at the gap. Nonetheless, two clear intervals could be always defined at any \( \theta_{bend} \) in the study. This implied that the bent array still obeyed the frequency dependence of the straight array, with minor changes due to the reshaping at the bending region.

Ideally, CROW studies are performed onto samples with long static chains, with a fixed illumination wavelength from one end of the chain. The transmittance is measured at the other end for loss-estimates. While our experimental system conclusively provides evidence for the existence of carrier modes in the bent amplifying array, its dynamic nature rules out loss estimates. Therefore, we take resort to finite difference time domain calculations, where we simulate an ideal experimental situation wherein an array of non-touching resonators with gain is illuminated with a possible...
carrier mode. The propagation characteristics of the mode are then described. These calculations were focused only on studying spatial behavior and not the spectral behavior. The calculations were implemented through the well-acknowledged, freely available software MEEP.27 The spatial resolution was maintained dx = dy = 1/15 μm, and the temporal resolution was 0.11 fs, in real units. Altogether, the computational mesh size was 390 μm by 125 μm, for the largest bend angle. The large system size restricted our calculations to two-dimensions. Nonetheless, the main points of study, i.e., bending in non-contact chains and effects of spherical surfaces, were well served by these calculations. Here, we discuss the generic propagation features by illustrating the periodic configuration, but these were also confirmed for deliberately added disorder. The system consists of a series of 15 infinite identical cylinders of diameter 18 μm (refractive index $n' + in'' = 1.34 - 0.002i$) separated by 6 μm. The negative imaginary component to the refractive index was added to implement unsaturable optical gain.

It should be emphasized that, in the experiments, the green excitation was made incident uniformly onto the array, which created population inversion in the droplets leading to gain. In the FDTD, the excitation was not explicitly simulated, but was rather implemented as uniform gain by main- 

The developing nanojet at the edge of the first cylinder breaks into a series of transverse maxima and minima (Fig. 4(b)). These maxima propagate along the axis in the form of filaments and are coupled to the subsequent cylinders, where they get refocused into a nanojet. For this configuration, the next nanojet is realized at the sixth cylinder, as seen in the image (Fig. 4(a)). The mode propagation occurs via repeated jet formation and filamentation. Interestingly, similar behavior was reported in Ref. 6, which discusses ray propagation in chains of very large spheres ($D \gg 10\lambda$). In these calculations, after about 18 spheres, the transported rays are seen to bunch together in discrete bunches along the axis of the array. It would be of interest to verify whether these bunches are the ray-counterpart of the nanojet filaments observed in our calculations. These filaments affect the coupling at the bends, as seen in Fig. 4(c) ($\theta_{\text{bend}} = 30^\circ$, white dots mark the bend). The figure illustrates the significant radiative loss due to bending. Since the transverse intensity profile is not uniform due to the filamentation, the coupling does not vary monotonically with bending angle. Figure 4(d) shows the situation as in Fig. 4(c), but with optical gain revealing enhancement of the intensity and compensation of the bending loss. Figure 4(e) depicts the intensity along the chain for $\theta_{\text{bend}} = 0^\circ$ (black), $10^\circ$ (red), and $15^\circ$ (blue). The shaded region labels the bend. The black curve shows a gradual decay indicating normal radiative losses in direct-coupling. The red and blue curves show that the bending loss actually occurs over about 5-6 spheres before the decay is determined by normal radiative losses. Furthermore, an interesting propagation feature of the mode

between the cylinders, the nanojet formed at the edge of the first cylinder breaks into filaments outside, seen in the magnified image (b). (c) Bent array $\theta_{\text{bend}} = 30^\circ$, showing the details of bending loss and propagation. (d) Same array under amplification, showing intensity enhancement and the self-correcting propagation. (e) Intensity distribution along the array in three passive arrays, $\theta_{\text{bend}} = 0^\circ$, $10^\circ$, and $15^\circ$. (f) Same, in active arrays. (g) Termination intensity as a function of $\theta_{\text{bend}}$, showing loss compensation by about 2 dB.
in this system is seen in Figure 4(d). After the bend, the mode tends to get channeled away from the axis. But the lensing effect realized by the spherical shape redirects the mode back into the array. As a net result, subsequent propagation does not occur axially, but rather along a reptilian path about the axis. Thus, the spherical shape triggers a self-correcting mechanism that prevents excessive loss even when \( \theta_{\text{bend}} \) is large. Figure 4(f) describes the compensation of the losses by the gain, wherein about 2 dB of improvement is observed in the transmitted intensity. Apart from the periodic chains, we also simulated disorder in sizes and separations, and observed the same generic spatial features listed above. While the disorder can be expected to affect the spectral behavior, the spatial features of the NIM modes in non-touching spheres are rather insensitive to the disorder.

In summary, we have implemented small-angle bending in a chain of amplifying spherical resonators that sustains NIM-based modes. We measure the frequency response and the modal density in the bent arrays. 2D FDTD calculations of transmittance in non-contact chains reveal that transport is mediated by filamentation of nanojets. A self-correcting propagation mechanism is realized by the spherical shape of the resonators. The study reveals the potential of such a system in making bent aCROW’s (active CROW’s). The fluidic nature of our system is ideally suited towards applications in optofluidic systems.28

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26This was measured using a time-gating technique.