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**00:00**

I'm going to use exactly what I show you, so that's why the introduction was super long in the previous talk. But I'm going to use everything that I shown you, actually, to explain what happened with collision. And so as a very quick recap-- it's going to be super fast. So the whole point is show you that you have a discrepancy between phase and group velocity of the dissipative Kerr soliton, and you can recast it in a single frequency, like you see here.

**00:23**

You have [INAUDIBLE] mixing in the dimension, and [INAUDIBLE] you have a two dimension-- you have a 2D comb that can be produced. So far so good, but nobody asked me actually about the binding of the group velocity. You just assume, fine, group velocity is [INAUDIBLE] together. Everything works well. That's a very big assumption here, and most of the time, that's not true.

**00:50**

And actually, there's many, many, many work that has been carried by-- here is a work by Tobias Kippenberg, where actually was group velocity is actually not binding at all. And actually, you can either make them travel together, or you can just make them not travel together at all. So that's really something you can actually play with. And also, I told you, in the application level, you have many, many things, and metrology, although we are very focused on at NIST, that's not the only thing in life.

**01:18**

You can do much, much, much more with frequency comb. In particular, you have a lot of application where having multiple repetition rate using dual comb spectroscopy, for instance, can be very interesting, but also for low noise microwave, for current communication, neutron fast measurement, and all this kind of thing can actually harness multiple repetition rate together. So dual comb actually is become very, very, very huge, in particular, because of [INAUDIBLE] spectroscopy.

**01:50**

And one thing that is very interesting about, when you have two repetition rate, is actually you're going to alias it, which means that you're going to basically transfer your optical frequency comb into a microwave frequency comb automatically because of the [INAUDIBLE],, which means that, if you actually have a spectroscopy that is in the optical domain, you can very easily measure it in the microwave domain.

**02:13**

And it has been shown recently, and that's actually one of the reasons why we're actually interested about the dual repetition rate, is that you can actually, with this aliasing, a frequency division of the repetition rate. Which means, in this case-- which is a very nice paper on Nature Com. I invite you to read it. You can actually measure your repetition rate indirectly because it's going to be divided by the number of countries that are in between.

02:42

But both of these systems rely on multiple rings, so that means you have to soliton that are independent, and you basically combine them only in waveguide, fiber, whatever you want. And most of the time, you have two laser in this case. One laser in this case. Can you do it in a single resonator? Can you have two solitons that travel not at the same repetition rate in a single resonator?

03:06

That's going to lead to collision. Obviously, if you have one [INAUDIBLE] the other, at some point, they're just going to collide because they just run around the resonator. That's not something new. Collision has been studied for decades. [INAUDIBLE] and there's way too much stuff about collision happening, especially in the 90s, and it's kind of amazing.

03:26

But there's a lot of [INAUDIBLE].. And there's this recent work actually, relatively recent work by [INAUDIBLE] group that actually studied the dynamic of dissipative Kerr soliton that can collide. And in this work, it's very interesting because they see a lot of dynamics. They see merging of it on nuclear DKS. That also has been demonstrated by Tobias Kippenberg.

03:47

They have DKS hopping. They have DKS that just vanish. They have DKS annihilation, when one is still alive, and the other one is killed. And they keep most of the dynamic of soliton collision has been observed in resonator, and that's really interesting, but most of this collision also has been observed with carrier the dissipative Kerr solitons that are very close to each other.

04:12

That mean they are regenerated as [INAUDIBLE] our way. So I didn't find the paper. I don't even know if there's a paper. If there's a paper, please tell me. That's Maxim that presented that at CLEO. I remember that at CLEO. I couldn't find the paper, where basically, he sent multiple laser, 1,550, [INAUDIBLE],, and he show that he can have two soliton inside.

04:32

And what you say is, well, you can actually do spectral multiplexing of your soliton, and that's very interesting. But he didn't see anything relative to the collision, and [INAUDIBLE] start to be interesting. That mean, when you kind of put them close together at the same kind of frequency, you obviously have a very rich dynamic. Waves are far, far away from each other, and they don't actually have very much overlap.

04:54

You basically don't see much. So as I say, collision in soliton has been something that has been studied since the 90s, and in particular, because telecom. And soliton have been huge for telecom during the bubble for propagating information, and as you can

imagine, if you send multiple soliton at a different repetition rate in the same fiber, at some point, they're going to collide and might start to do some nasty stuff that can be annoying for telecom.

**05:22**

In particular, in this paper actually, is the highlight that the collision can yield for a mixing process. And so they go on and on explaining how they don't want that, and the point is, it hasn't been seen in ring resonators. It's kind of [? like four-wave ?] mixing that result from the collision. So the point is, can we actually see this kind of dynamic that hasn't been observed in ring resonator?

**05:48**

So quick reminder, the single frequency from the soliton, so soliton, you [INAUDIBLE] envelope, fast oscillation. Drift at a different velocity because phase velocity different from velocity. So that mean all this fixed point in the azimuthal angle oscillate at the same period that falls at the same frequency. What if you have a soliton that don't have-- that doesn't have the same velocity?

**06:16**

That mean you're going to have both these phase velocities are different, and the group velocity is different. Same thing-- we actually pick, here, points that are fixed in this [INAUDIBLE] domain. As you can see, they're going to oscillate, but the oscillation is going to be damped because of the envelope. So what you will get here-- I'll only pick one here.

**06:34**

You're actually going to get the oscillation at the fixed frequency because of the discrepancy between group and phase velocity, but also an envelope, which means that if you do a Fourier transform, you do not only get one frequency. You get, actually, multiple frequency. That's very interesting because, if you recall the first talk, I told you, [INAUDIBLE] actually have one pump here, one pump there, you get an OPA, et cetera, et cetera.

**06:55**

What's actually happening, if you have a dissipative Kerr solitons that travel at the different velocity, group velocity, then you also have solitons [INAUDIBLE].. You have a multi pump system. I had to fix repetition rate here. That is defined by the discrepancy of the two group velocity, and that's one of the findings I didn't mention in the previous talk. four-wave mixing, Bragg scattering.

**07:19**

Bragg scattering is when you have two pump, they create a modulation of the refractive index, and essentially, translate in frequency the signal into new idler on the other side of the pump. It's kind of what you can see happening here. [INAUDIBLE] going to have this effectively multipoint system, so it's going to translate and create new idler around your frequency pump. So we can simulate this thing.

**07:43**

I'll show you [INAUDIBLE] working actually pretty well for this stuff. We simulate using integrated dispersion, which is actually very close from the one that we measured. Pump it at 193 hertz, [INAUDIBLE] we are 283 hertz, or 1,550, 162 nanometer, and we generate two soliton. They're in the same resonator. One here is filtered, so you can easily filter them [INAUDIBLE]..

**08:10**

So you can get one or the other soliton because they're far away from each other. And what we see is, when they are independent, they kind of look like regular soliton. When they collide, you can see, well, other collisions, there is weird stuff. Definitely some phase business is happening here. But more interestingly, also [INAUDIBLE] the propagation. What you see here, you see these tribes of each of the soliton that creates this modulation.

**08:36**

It's kind of reminds you of a [INAUDIBLE],, but the thing that is interesting is this kind of tribes here are actually parallel to the trajectory of those [INAUDIBLE].. Something [INAUDIBLE] extracted periodically, every round trip. Recreate your pulse train. Get the frequency comb, and we plot in this 3D type of stuff. And what you can see, you see very well, this dark blue here, this second pump frequency comb, the first pump frequency comb.

**09:05**

Obviously, they have different repetition rates. Those are not parallel, but what you can see is also, all these frequency components that are here and here. If we do the integral in this new domain to actually get the FCO of the system, you have the secondary pumped soliton as a lot of frequency component, like I told you, is because drift is moving at a different group velocity, so as expected.

**09:30**

But this, in red, should only be one tone because it's a single soliton, so it's only-- it should have a fixed [INAUDIBLE].. But what you can see, you see all these different [INAUDIBLE] that are appearing that are exactly spaced as those [INAUDIBLE] soliton frequency spacing. So that mean, throughout this simulation, what I show you is that the collision between two soliton, it's equivalent to a four-wave mixing in this phase space.

**10:00**

That's kind of interesting because that mean, also, scanning what I showed you before, I mean, if you want to inject many, many, many, many, many, many, many pump, you do not have to have very, very many CW laser. You can honor this property actually and have different tools that do the same stuff. So why not? That's cool. I show you a lot of theory.

**10:17**

What about experiment? Here, what we're doing is we're creating a single DKS at 1,550, and actually, for reason to actually optically resolve better our result to actually create a DKS crystal, so many solitons that are tied together, and just we fill it with soliton. Here, there's 11 in the cavity, I believe. That actually is a red line. And what you can see right away is, around this red line, you already have some component, and you can already get some mixing happening over there.

**10:46**

We can effectively freeze-- that mean we need to pick a repetition, and we're going to basically freeze our main soliton. So what's going to happen is the other DKS crystals are going to travel in the cavity at a different speed. Plotting in this 3D domain, we see very well the primary comb here fixed at 0, which is our offset. The other one is a straight line, basically, that has a different frequency, different group velocity.

**11:14**

But what you can see already is all the different [INAUDIBLE].. If you plot it, if you integrate [INAUDIBLE],, like usual, what you will see, you will see in red, the DKS crystals that, as expected, has different comb teeth. But in addition to solitons, that should be a fixed [INAUDIBLE] because of the mixing in this phase velocity domain. Can do exactly the same by freezing instead the soliton crystal and not a single DKS.

**11:40**

So basically, what's happening is you take this [INAUDIBLE].. You just tilt it, and you're going to do the integrate [INAUDIBLE] integrating of [INAUDIBLE] dimension integrates over this dimension. That's what you're seeing here. And what you see is you should have-- you obviously have the single DKS that have new frequency component. Soliton crystal should have only one, and what you see is all the different components that are due to four-wave mixing.

**12:03**

And if you really push it hard, that the kind of comb that you're going to get. So you're going to get this kind of interwoven. It's kind of a fancy world. I'm not a native English speaker, so interwoven was a fancy word that I learn because my girlfriend was doing knitting, and that really remind me of that. But basically, the whole point that is important is that, in the output of your frequency comb, that each comb, each comb tooth will carry both repetition rate on average.

**12:35**

So that mean, not-- if you take a snapshot at a given time, you will get this comb tooth carrying one or the other. But on average, each comb tooth will carry both repetition rate. So can we see collision in a different way? So right now, I can't show you a lot of, oh, it's a [INAUDIBLE],, et cetera, et cetera. And so basically, what you see is still this viewpoint in this phase velocity domain, where you freeze your DKS so it's a single frequency.

**13:00**

You have the other one that has a different group velocity, so it's not a single frequency. It's many frequency component. And because of [INAUDIBLE] you translate this [INAUDIBLE] into the other one over there. But if you think about collision, I mean, that's undergrad type stuff. Elastic collision, where you have one particular moving, the other at rest, collide if you have full transfer of energy, et cetera, et cetera, et cetera.

**13:27**

The red one going to be at rest, and the other one moving. All right, now, let's have a look of what happens if you have a soliton one moving, one at rest. Let's say it behave like [INAUDIBLE] particle. This one is going to become at rest, and the other one's going to be moving. What does that mean? That means this one, that's the picture that we're used to, one fixed one, one moving.

**13:48**

Therefore, multiple frequency component. In the other case, that means this one become fixed. Only one frequency component. Here, let's say it's not perfectly transfer of energy, so it's still drifting a tiny bit. But this one is definitely moving. That mean you have all of these kind of frequency that start to happen just because we are not freezing-- it's not moving in the freezing referential [INAUDIBLE].

**14:10**

That's basically the same point of view. If you take into account the [INAUDIBLE] point of view, which is four-wave mixing backscattering, or a particular that basically bonds against each other, you see the same stuff. And I talk about [INAUDIBLE] made a lot of stuff. I'm done. I'm almost done. [INAUDIBLE] basically talk about a lot of stuff about how this, actually, frequency is [INAUDIBLE] quantum state of a soliton, and that's actually the [INAUDIBLE] frequency.

**14:43**

And that mean soliton is a quantum field of light, et cetera, et cetera, and basically behave as a quantum particle, and therefore, duality wave particle. That stuff that hasn't really been demonstrated experimentally, I believe, and so can we actually push it a bit further and actually use this type of collision to actually start to study this kind of duality wave particle of a soliton [INAUDIBLE]?

**15:07**

And so with that, I hope that I convinced you that the phase velocity can mix not only when you have group velocity binding, but basically all the time. And so that's mean you kind of need to take it into account, and that means, if you introduce multiple pump, you're going to have phase velocities that happen. And you can harness it into many, many, many different ways. I hope I convinced you, also, that if you have two DKS at two different  $f_{rep}$ , that's essentially being the same as one DKS with many auxiliary pumps, and that means you can really scale it up very easily if you want to inject multiple pump.

**15:39**

Collision, we can very well do it with [INAUDIBLE] where it seems to be very simple. But somehow, it's very powerful, and we show experimentally the collision that result for a mixing using one DKS and one soliton crystal. And so what's next? Can we use this kind of thing for metrology? [INAUDIBLE] all this kind of business? Can we do it?

**15:59**

Can we find application for spectroscopy? Because all of a sudden, you have this area where you have a huge density of comb teeth, and because they both carry both f rep, can you do some aliasing and stuff like that? That can be interesting for spectroscopy. And like I discussed, can we push further to see interesting physics, like wave particle duality, et cetera?

**16:16**

And with that, I'd like to thank the people that work on that, Kartik, Pradyoth and Curtis. And also chip I show you have been fabricated at Ligentec. That mean, if you have the money, you can make it. Thank you.