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(54) **TUNABLE OPTICAL CHANNEL SLICING AND STITCHING TO ENABLE DYNAMIC BANDWIDTH ALLOCATION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/890,211**

(22) Filed: **Feb. 6, 2018**

(65) **Prior Publication Data**

US 2018/0227071 A1 Aug. 9, 2018

Related U.S. Application Data

(60) Provisional application No. 62/456,517, filed on Feb. 8, 2017.

(51) **Int. Cl.**

H04B 10/50	(2013.01)
H04J 14/02	(2006.01)
H04B 10/572	(2013.01)
H04B 10/2507	(2013.01)

(52) **U.S. Cl.**

CPC ***H04B 10/506*** (2013.01); ***H04B 10/2507*** (2013.01); ***H04B 10/572*** (2013.01); ***H04J 14/0265*** (2013.01); ***H04J 14/0298*** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

(56) **References Cited**

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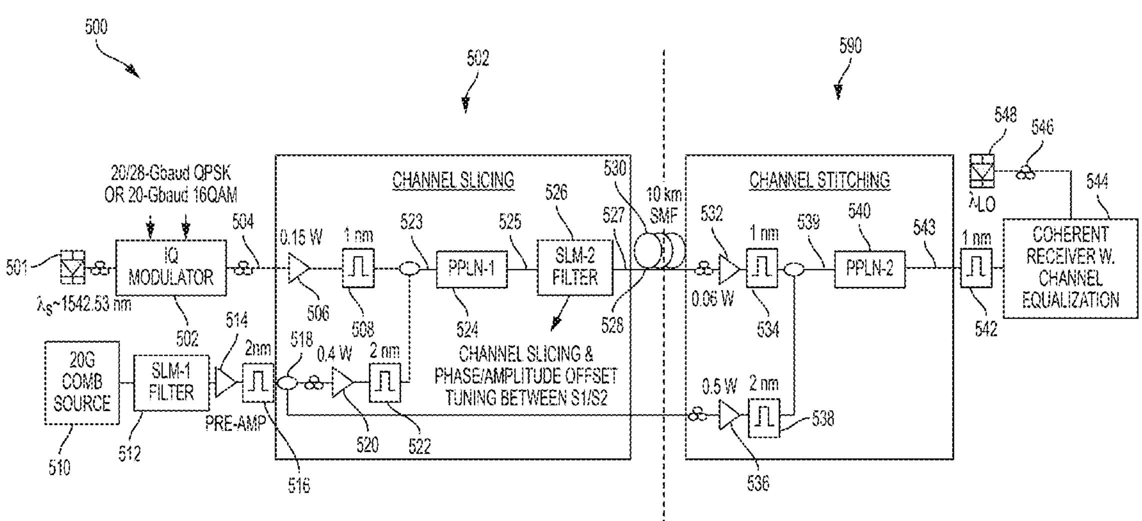
(74) *Attorney, Agent, or Firm* — Snell & Wilmer LLP

(57) **ABSTRACT**

A method for transmitting an optical signal through a first channel and a second channel includes coupling the optical signal with a first pair of comb lines separated by a spacing frequency to create an optical signal copy that is spaced from the optical signal by the spacing frequency. The method also includes filtering a first slice of the optical signal and a second slice of the optical signal copy. The method also includes transmitting the first slice of the optical signal and the second slice of the optical signal through the first channel and the second channel, respectively. The method also includes stitching the first slice of the optical signal with the second slice of the optical signal copy to generate a stitched version of the original optical signal.

17 Claims, 14 Drawing Sheets



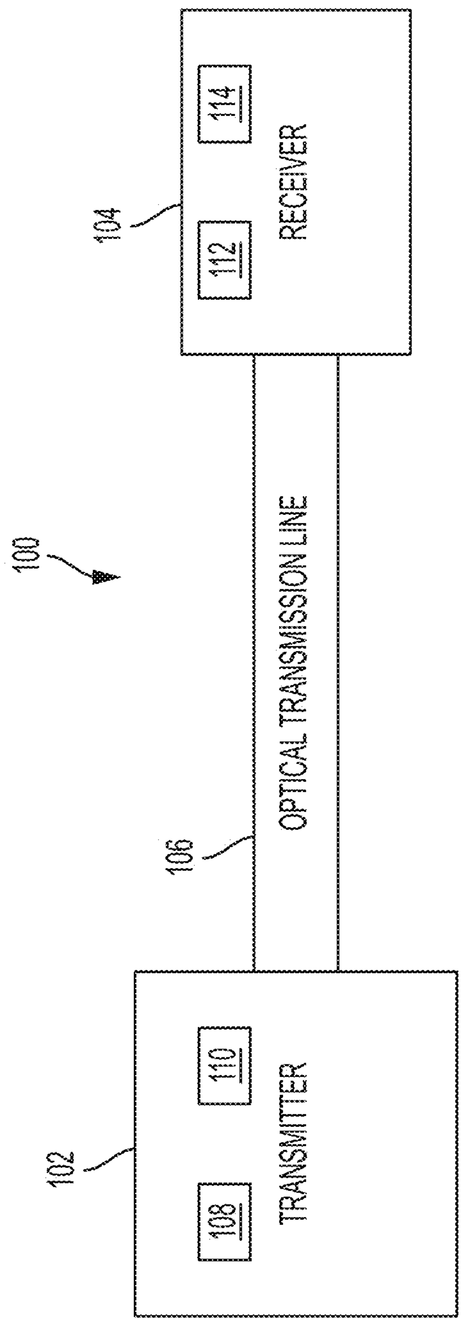

100
104
RECEIVER
112
114
OPTICAL TRANSMISSION LINE
106
102
TRANSMITTER
108
110

FIG. 1

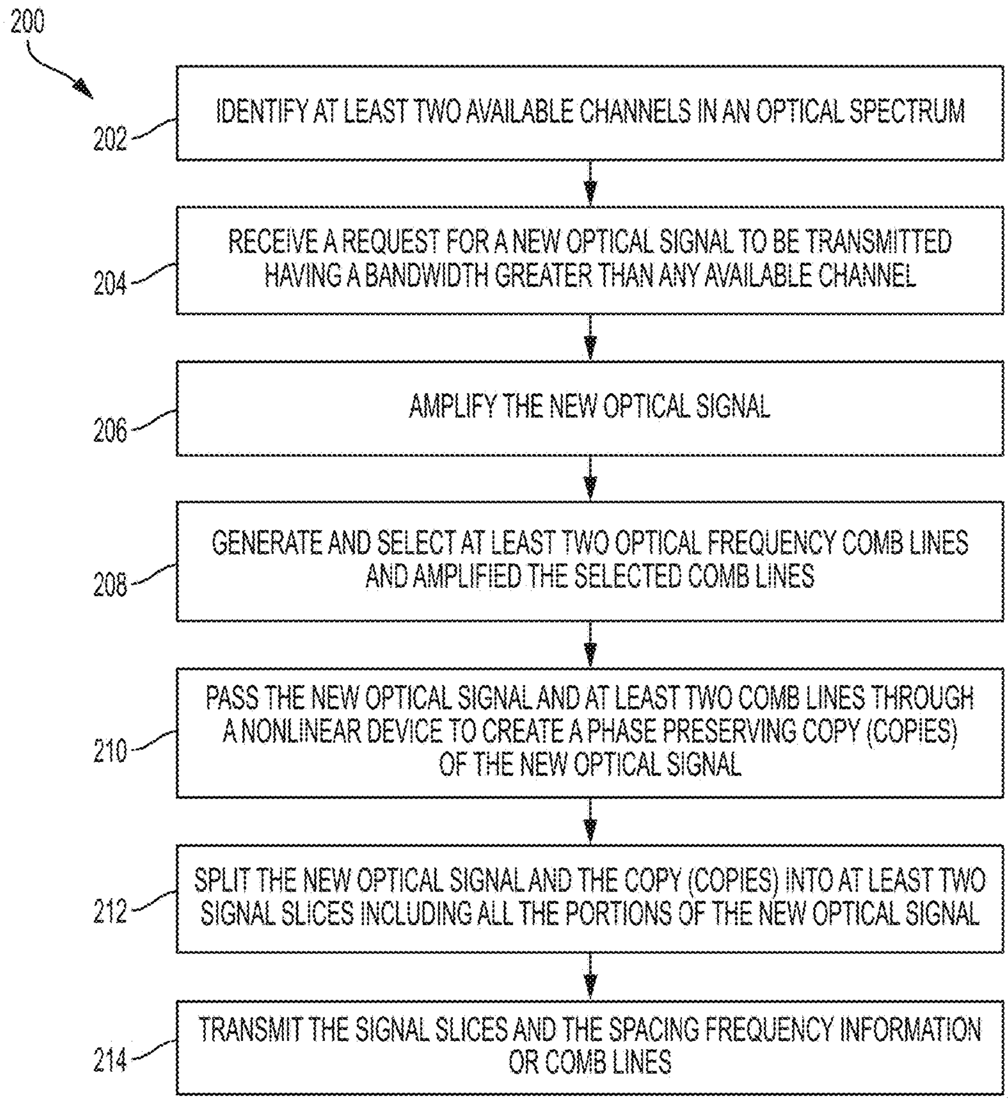

200
202
IDENTIFY AT LEAST TWO AVAILABLE CHANNELS IN AN OPTICAL SPECTRUM
204
RECEIVE A REQUEST FOR A NEW OPTICAL SIGNAL TO BE TRANSMITTED HAVING A BANDWIDTH GREATER THAN ANY AVAILABLE CHANNEL
206
AMPLIFY THE NEW OPTICAL SIGNAL
208
GENERATE AND SELECT AT LEAST TWO OPTICAL FREQUENCY COMB LINES AND AMPLIFIED THE SELECTED COMB LINES
210
PASS THE NEW OPTICAL SIGNAL AND AT LEAST TWO COMB LINES THROUGH A NONLINEAR DEVICE TO CREATE A PHASE PRESERVING COPY (COPIES) OF THE NEW OPTICAL SIGNAL
212
SPLIT THE NEW OPTICAL SIGNAL AND THE COPY (COPIES) INTO AT LEAST TWO SIGNAL SLICES INCLUDING ALL THE PORTIONS OF THE NEW OPTICAL SIGNAL
214
TRANSMIT THE SIGNAL SLICES AND THE SPACING FREQUENCY INFORMATION OR COMB LINES

FIG. 2

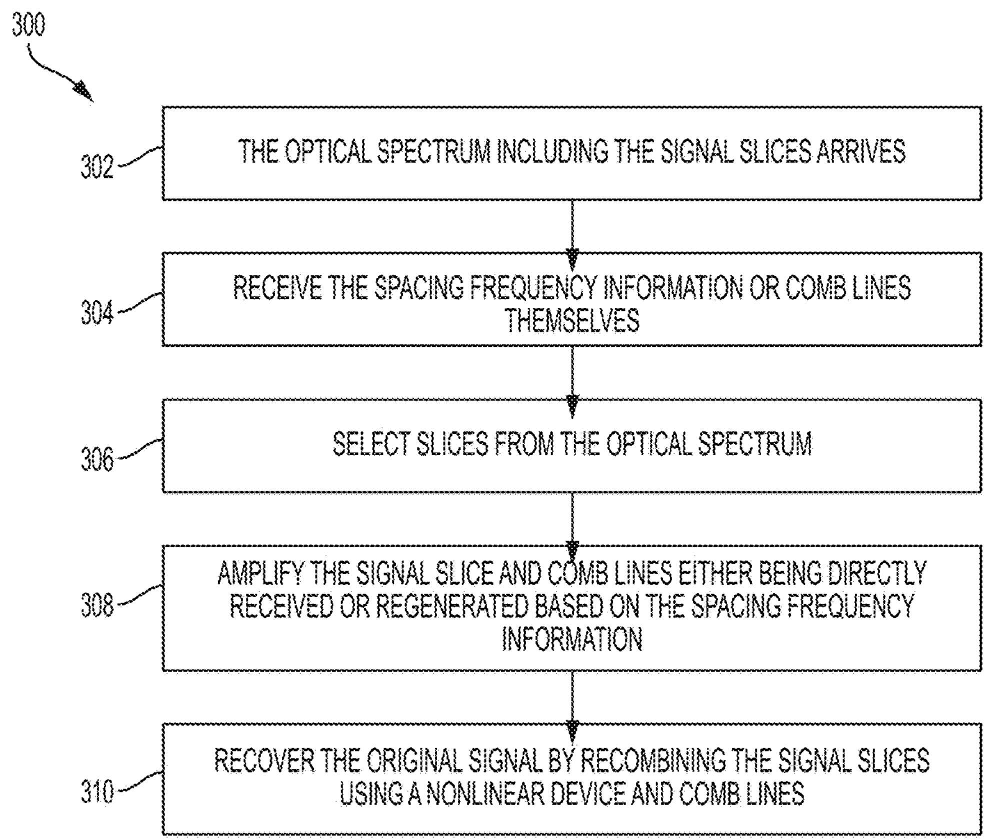

300
302
THE OPTICAL SPECTRUM INCLUDING THE SIGNAL SLICES ARRIVES
304
RECEIVE THE SPACING FREQUENCY INFORMATION OR COMB LINES THEMSELVES
306
SELECT SLICES FROM THE OPTICAL SPECTRUM
308
AMPLIFY THE SIGNAL SLICE AND COMB LINES EITHER BEING DIRECTLY RECEIVED OR REGENERATED BASED ON THE SPACING FREQUENCY INFORMATION
310
RECOVER THE ORIGINAL SIGNAL BY RECOMBINING THE SIGNAL SLICES USING A NONLINEAR DEVICE AND COMB LINES

FIG. 3

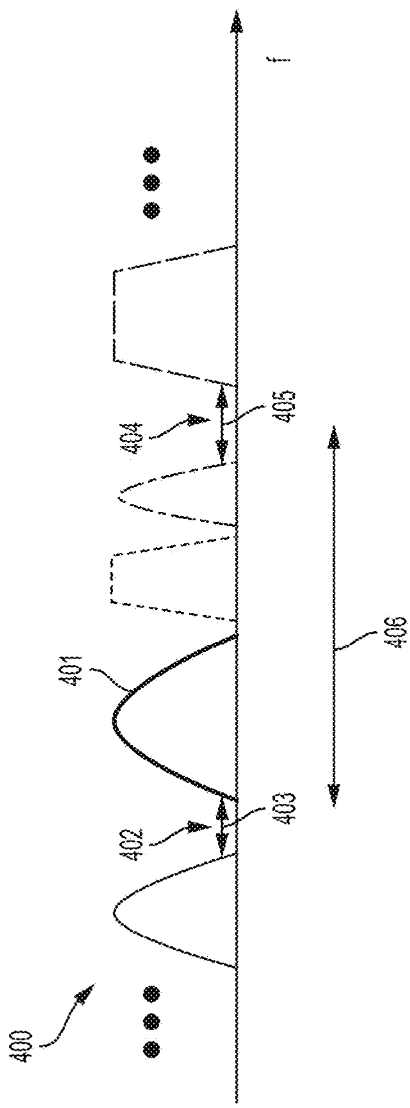


FIG. 4A

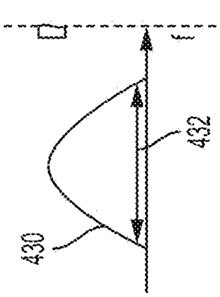


FIG. 4B

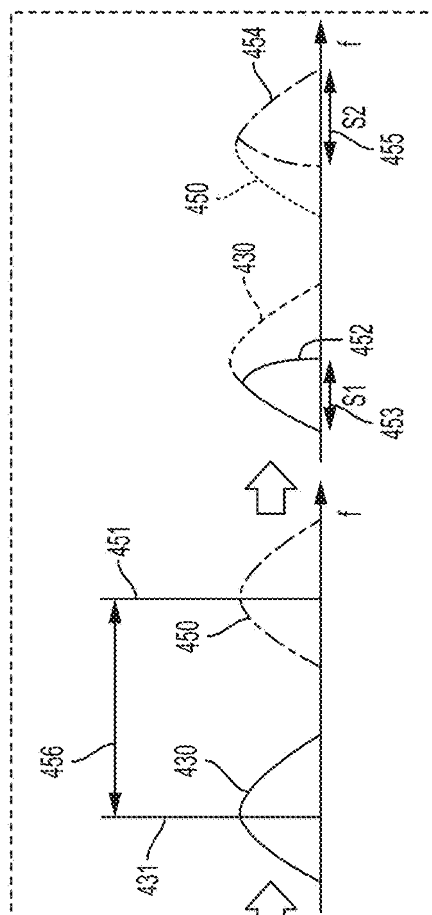


FIG. 4C

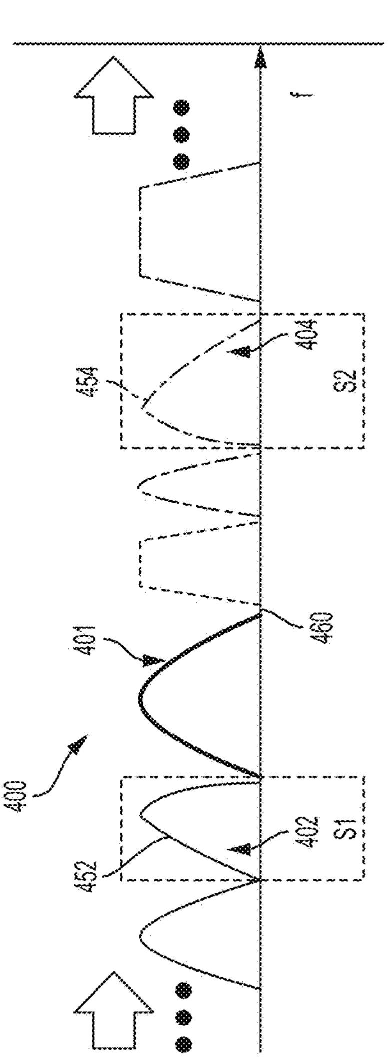

400
401
452
402
S1
480
454
404
S2
f

FIG. 4D

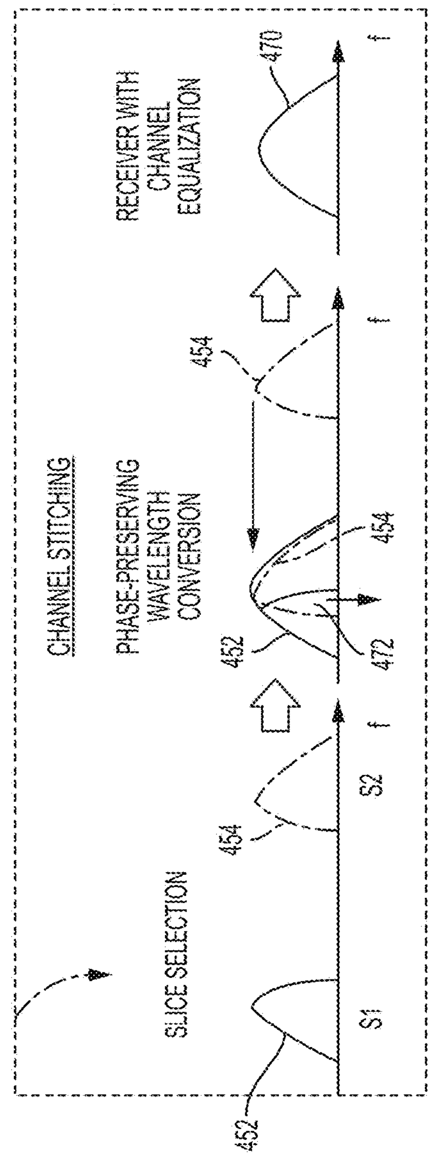

SLICE SELECTION
452
S1
454
S2
f
CHANNEL STITCHING
PHASE-PRESERVING
WAVELENGTH
CONVERSION
452
472
454
454
f
RECEIVER WITH
CHANNEL
EQUALIZATION
470
f

FIG. 4E

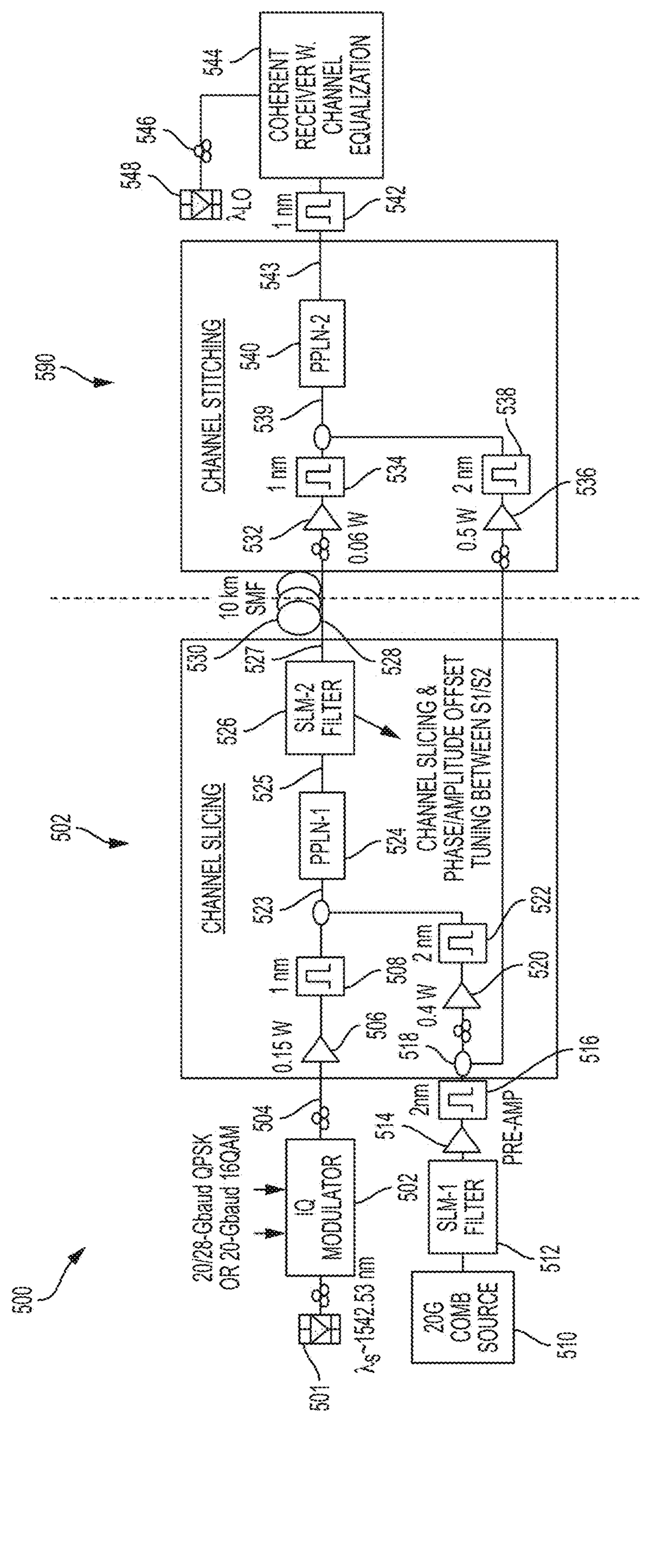

500
501
λs~1542.53 nm
20/28-Gbaud QPSK
OR 20-Gbaud 16QAM
IQ
MODULATOR
502
504
20G
COMB
SOURCE
510
SLM-1
FILTER
512
514
PRE-AMP
2nm
516
502
CHANNEL SLICING
0.15 W
506
1 nm
508
518
0.4 W
520
2 nm
522
523
PPLN-1
524
525
SLM-2
FILTER
526
CHANNEL SLICING &
PHASE/AMPLITUDE OFFSET
TUNING BETWEEN S1/S2
527
528
530
10 km
SMF
590
CHANNEL STITCHING
532
0.06 W
1 nm
534
0.5 W
536
2 nm
538
539
PPLN-2
540
543
1 nm
542
λLO
548
546
544
COHERENT
RECEIVER W.
CHANNEL
EQUALIZATION

FIG. 5

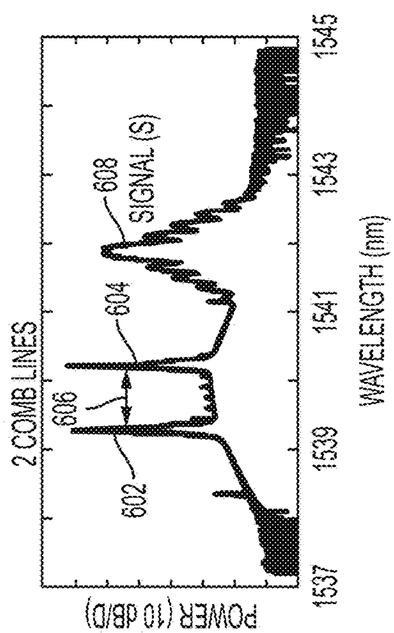


FIG. 6A

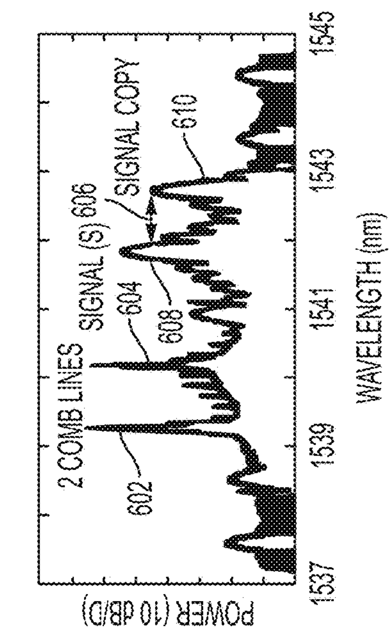


FIG. 6B

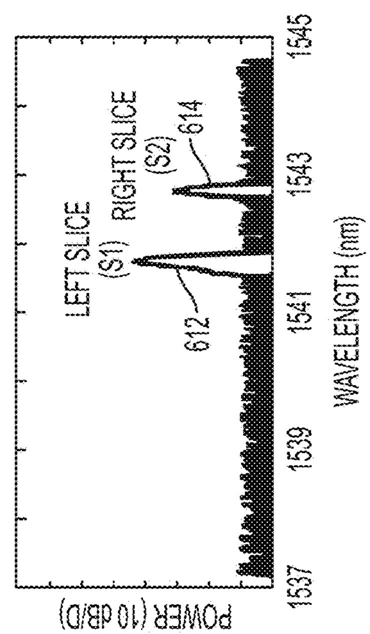


FIG. 6C

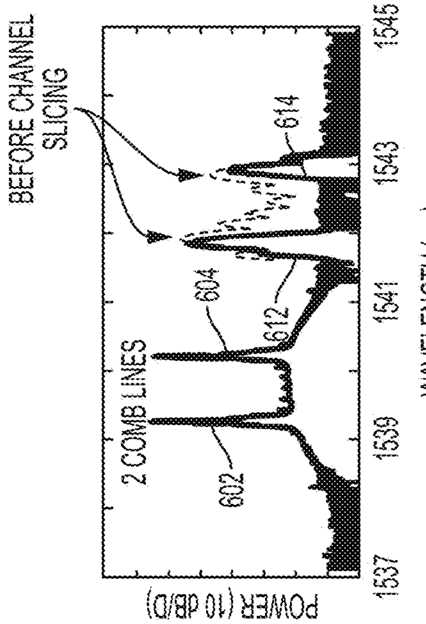


FIG. 6D

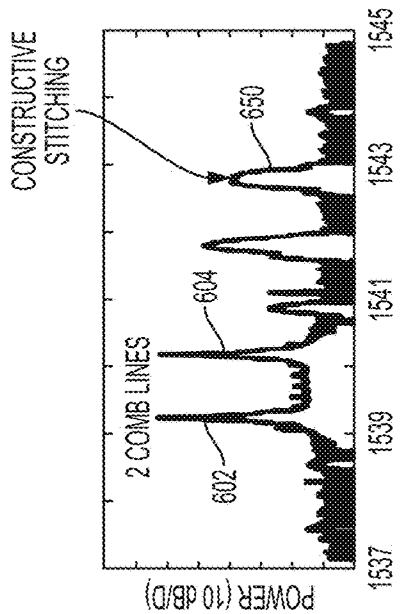


FIG. 6E

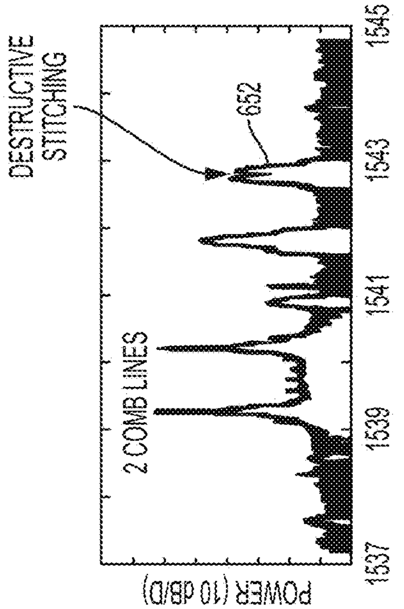


FIG. 6F

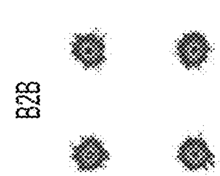


FIG. 7A

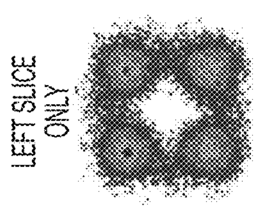


FIG. 7B

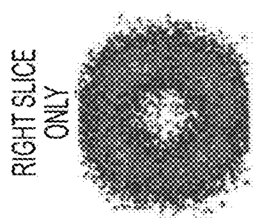


FIG. 7C

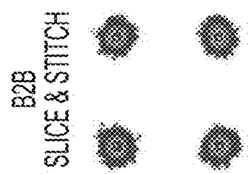


FIG. 7D

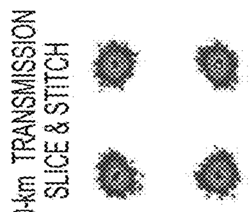


FIG. 7E

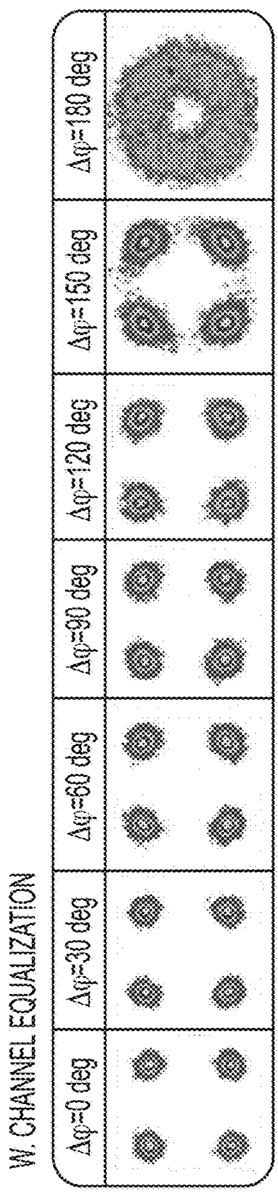


FIG. 8A

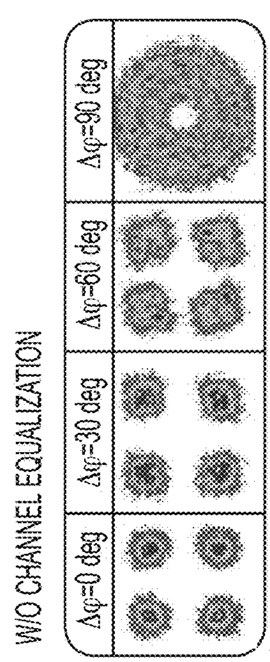


FIG. 8B

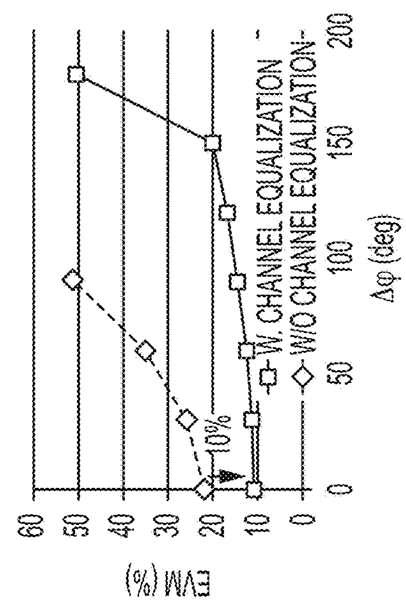


FIG. 8C

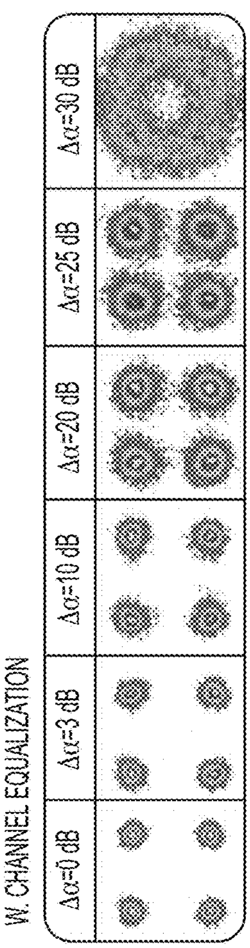


FIG. 9A

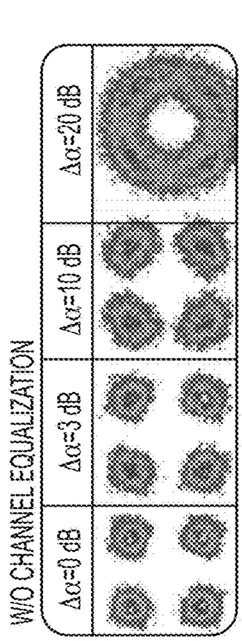


FIG. 9B

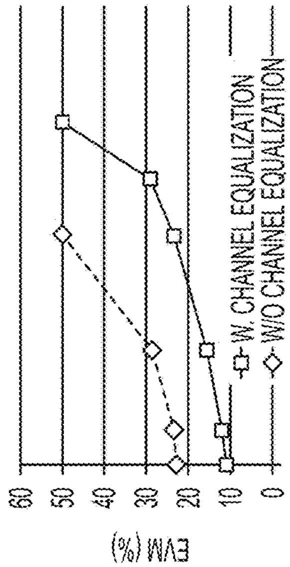


FIG. 9C

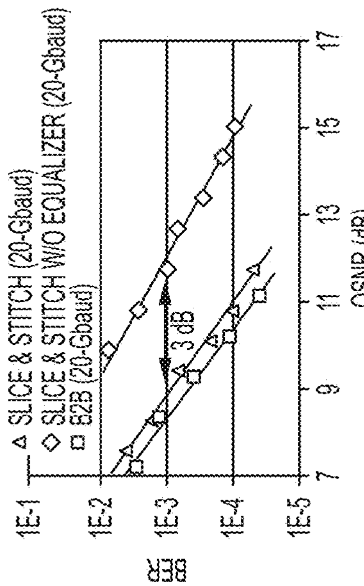


FIG. 10A

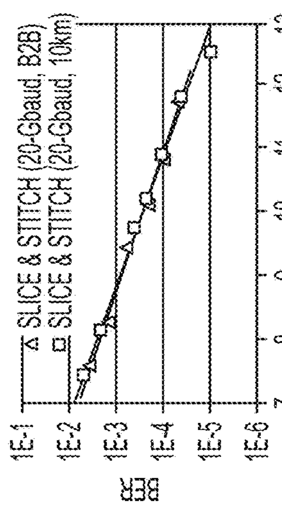


FIG. 10B

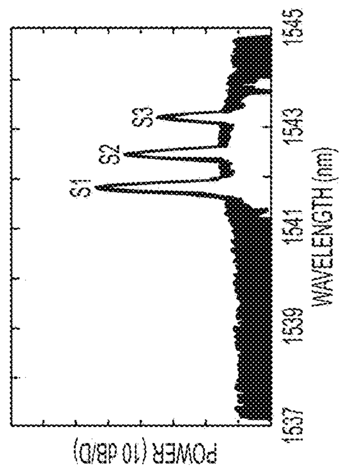


FIG. 11B

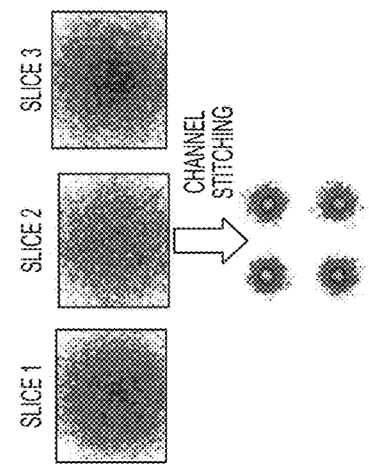


FIG. 11D

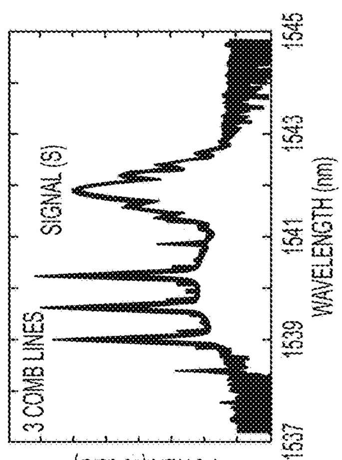


FIG. 11A

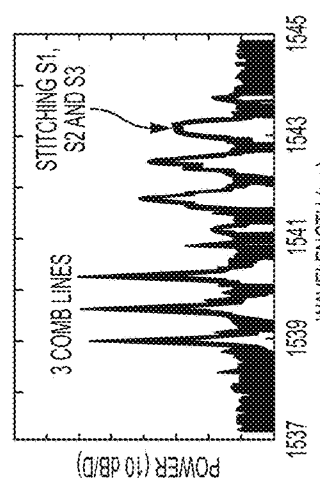


FIG. 11C

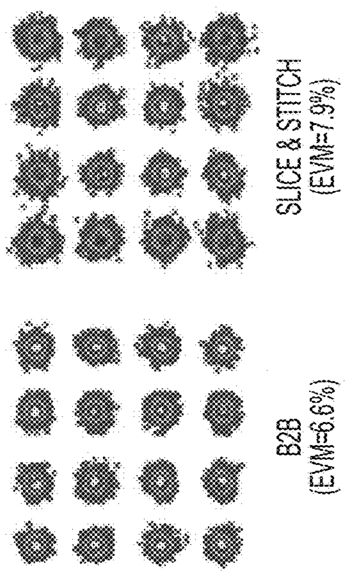


FIG. 13A

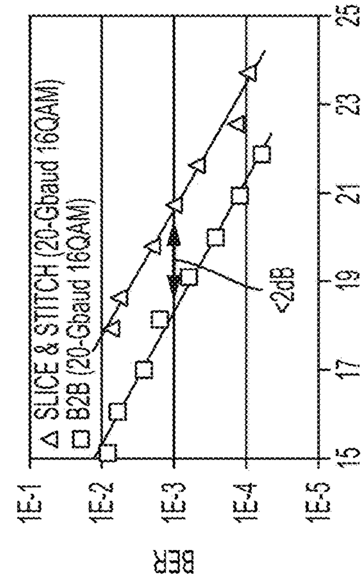


FIG. 13B

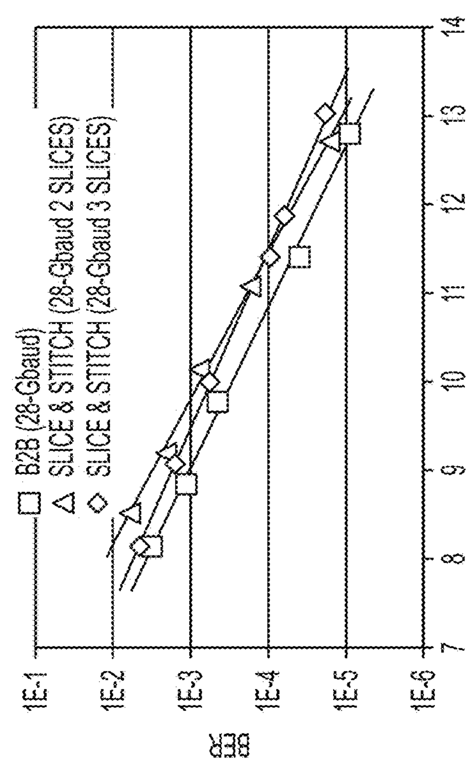


FIG. 12

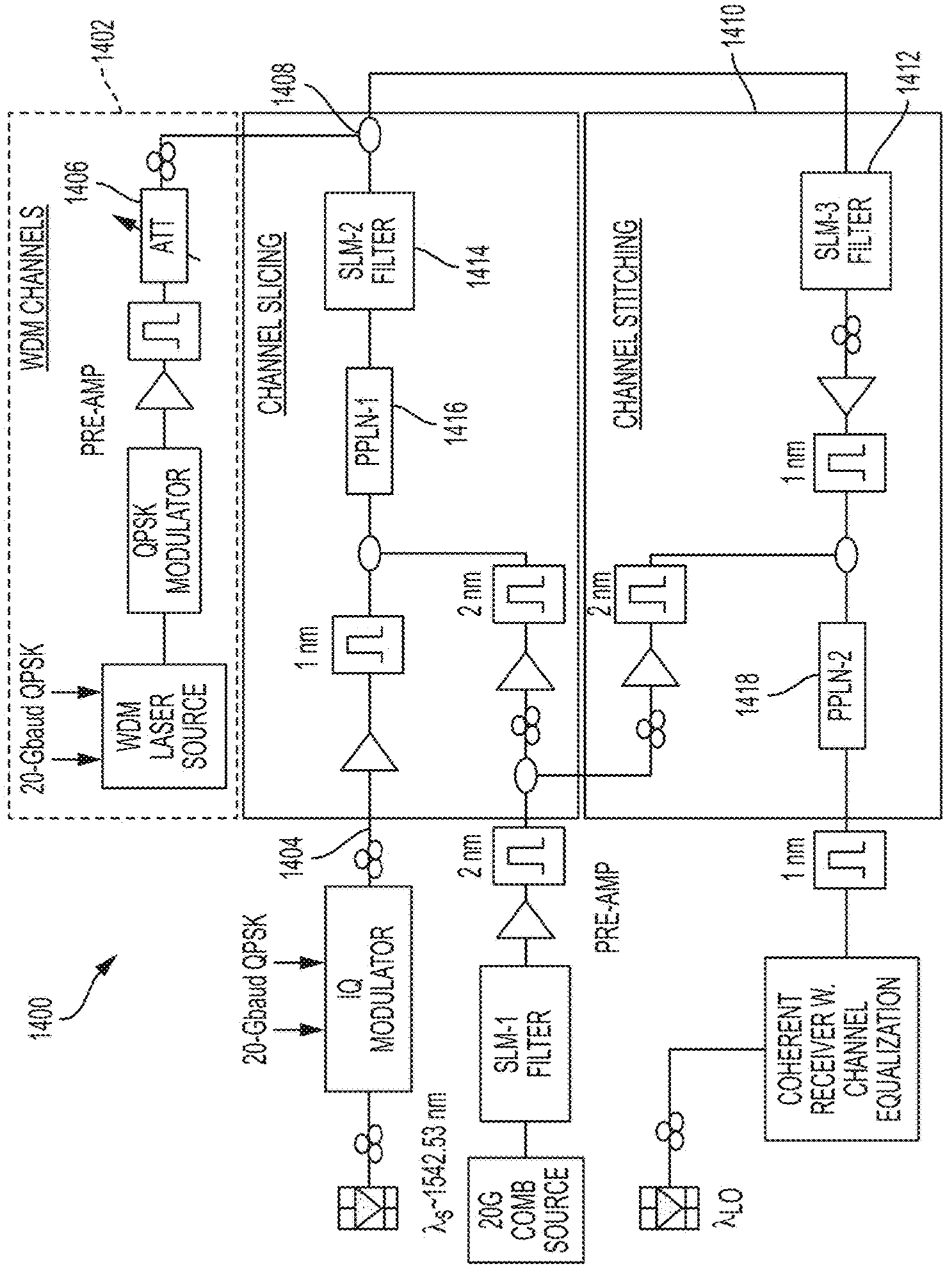

1400
1402
WDM CHANNELS
20-Gbaud QPSK
WDM LASER SOURCE
QPSK MODULATOR
PRE-AMP
ATT
1406
1408
1410
1412
CHANNEL SLICING
SLM-2 FILTER
1414
PPLN-1
1416
1 nm
2 nm
CHANNEL STITCHING
SLM-3 FILTER
1 nm
2 nm
PPLN-2
1418
1404
20-Gbaud QPSK
IQ MODULATOR
λS~1542.53 nm
2 nm
PRE-AMP
SLM-1 FILTER
20G COMB SOURCE
1 nm
COHERENT RECEIVER W. CHANNEL EQUALIZATION
λLO

FIG. 14

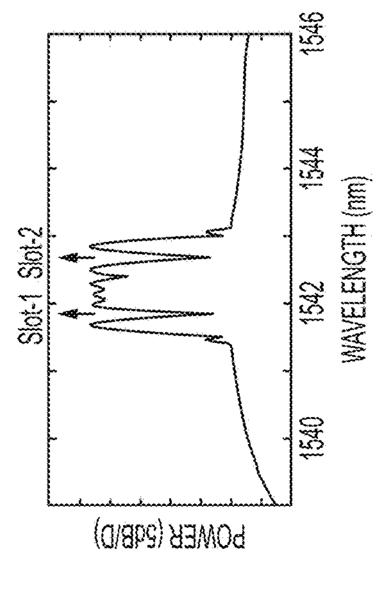


FIG. 15A

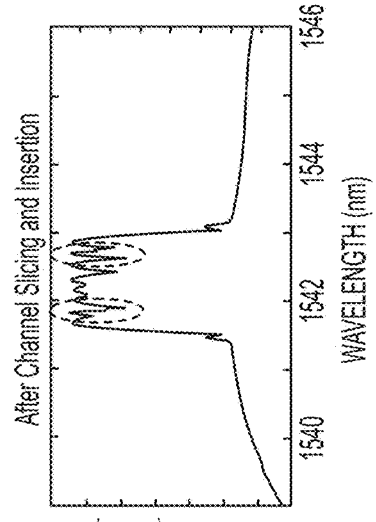


FIG. 15B

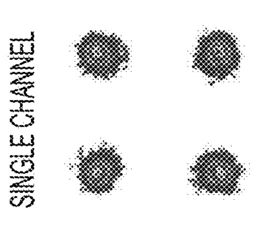


FIG. 16A

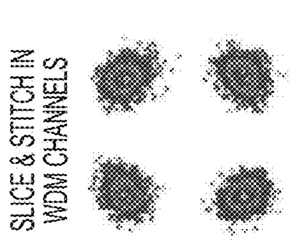


FIG. 16B

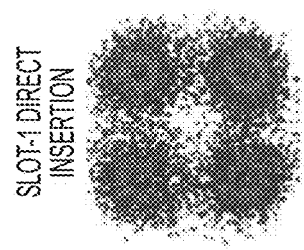


FIG. 16C

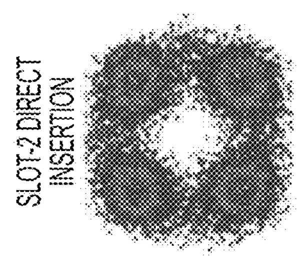


FIG. 16D

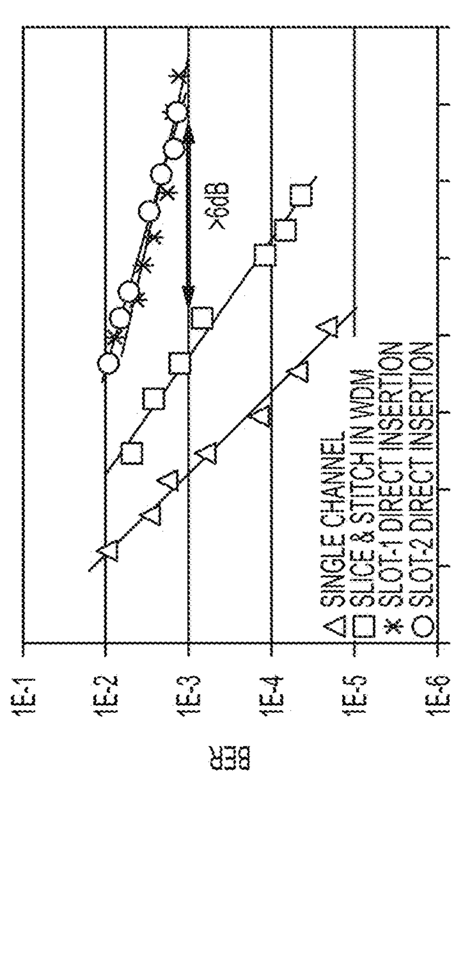


FIG. 17

TUNABLE OPTICAL CHANNEL SLICING AND STITCHING TO ENABLE DYNAMIC BANDWIDTH ALLOCATION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit and priority of U.S. Provisional Application No. 62/456,517, entitled "TUNABLE OPTICAL CHANNEL SLICING AND STITCHING TO ENABLE DYNAMIC BANDWIDTH ALLOCATION," filed on Feb. 8, 2017, the entire disclosure of which is hereby incorporated by reference herein in its entirety.

BACKGROUND

1. Field

The present disclosure is directed to systems and methods for slicing optical signals, inserting them into available slots in an optical spectrum, transmitting them via a transmitter, and stitching the signal together at the receiver.

2. Description of the Related Art

Optical transmission lines are becoming popular due to the relatively large bandwidth they provide. Many different signals may be simultaneously transmitted along an optical transmission line so long as an available slot has a sufficient bandwidth to accept the new signals. However, it may occasionally be desirable to transmit a signal on an optical transmission line that has a greater bandwidth than any single available slots on the optical transmission line. However, the total bandwidth of the available frequency slots may be larger than the new optical signal. Therefore, it is desirable to develop systems and methods for transmitting the new optical signal through discrete available transmission frequency slots.

SUMMARY

Described herein is a method for transmitting an optical signal through a first channel and a second channel that are separated by a spacing frequency. The method includes coupling the optical signal with a first pair of spacing coherent optical frequency comb lines separated by the spacing frequency to create an optical signal copy that is spaced from the optical signal by the spacing frequency. The method also includes filtering a first slice of the optical signal and a second slice of the optical signal copy, the first slice representing a first portion of the optical signal and the second slice representing a second complementary portion of the optical signal. The method also includes transmitting the first slice of the optical signal and the second slice of the optical signal copy through the first channel and the second channel, respectively. The method also includes stitching the first slice of the optical signal with the second slice of the optical signal copy to generate a stitched version of the original optical signal.

Also disclosed is a method for transmitting an optical signal. The method includes identifying, at a transmitter, at least two available channels in an available optical spectrum each having an available bandwidth. The method also includes receiving, at the transmitter, a request for a new optical signal having a signal bandwidth that is greater than the available bandwidth of either (or both) of the at least two available channels. The method also includes splitting, at the transmitter, the new optical signal into at least two signal slices each capable of fitting into the available bandwidth of one of the at least two available channels. The method also includes transmitting, by the transmitter, the at least two signal slices to a receiver. The method also includes receiving, by a receiver, the at least two signal slices. The method also includes stitching together, at the receiver, the at least two signal slices to generate a stitched version of the new optical signal.

Also disclosed is a system for transmitting an optical signal. The system includes a transmitter. The transmitter is designed to identify at least two available channels in an available optical spectrum each having an available bandwidth. The transmitter is also designed to receive a request for a new optical signal having a signal bandwidth that is greater than the available bandwidth of either of the at least two available channels. The transmitter is also designed to split the new optical signal into at least two signal slices each capable of fitting into the available bandwidth of one of the at least two available channels. The transmitter is also designed to transmit the at least two signal slices onto an optical transmission line. The system also includes a receiver. The receiver is designed to receive the at least two signal slices via the optical transmission line. The receiver is also designed to stitch together the at least two new channels to generate a stitched version of the new optical signal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a system for slicing and stitching an optical signal for transmission on an optical transmission line according to an embodiment of the present invention;

FIG. **2** is a flowchart illustrating a method for slicing an optical signal to fit the optical signal within available transmission slots according to an embodiment of the present invention;

FIG. **3** is a flowchart illustrating a method for stitching optical signal slices at a receiver according to an embodiment of the present invention;

FIGS. **4**A-**4**E are representations of an optical spectrum, a new optical signal to be transmitted along a transmission line, and slicing of the optical signal to fit within available slots of the optical spectrum according to an embodiment of the present invention;

FIG. **5** is a system illustrating a method for transmitting an optical signal through a first channel and a second channel that are separated by a spacing frequency according to an embodiment of the present invention;

FIGS. **6**A-**6**F are graphs illustrating various stages of the optical signal throughout the system of FIG. **5** according to an embodiment of the present invention;

FIGS. **7**A-**7**E are constellation comparisons of a 20 Gbaud QPSK channel under different scenarios according to an embodiment of the present invention;

FIGS. **8**A-**8**C are constellation comparisons of a 20 Gbaud QPSK channel under different phase offsets according to an embodiment of the present invention;

FIGS. **9**A-**9**C are constellation comparisons of a 20 Gbaud QPSK channel under different amplitude offsets according to an embodiment of the present invention;

FIGS. **10**A and **10**B are bit error rate comparisons for a 20 Gbaud QPSK system with and without equalization, and back-to-back and over a transmission line according to an embodiment of the present invention;

FIGS. **11**A-**11**D illustrate channel slicing and stitching with three slices for a 28 Gbaud QPSK system according to an embodiment of the present invention;

FIG. **12** illustrates a bit error rate comparison with various quantities of channel slices according to an embodiment of the present invention;

FIGS. **13**A and **13**B illustrate EVM comparison between back to back and channel slicing and stitching for a 20 Gbaud 16-QAM signal, and a bit error rate comparison according to an embodiment of the present invention;

FIG. **14** illustrates a system for fragmented bandwidth allocation in 6 WDM channels each channel with 20 Gbaud according to an embodiment of the present invention;

FIGS. **15**A and **15**B illustrate measured spectrums before and after fragmented bandwidth allocation, respectively, according to an embodiment of the present invention;

FIGS. **16A-16D** illustrate a constellation comparison between direct channel insertion and fragmented bandwidth allocation enabled by channel slicing and stitching according to an embodiment of the present invention; and

FIG. **17** illustrates bit error rate comparison between direct channel insertion and fragmented bandwidth allocation enabled by slicing and stitching according to an embodiment of the present invention.

DETAILED DESCRIPTION

Referring to FIG. **1**, a system **100** for transmitting optical signals is shown. The system **100** includes a transmitter **102**, a receiver **104**, and an optical transmission line **106**. The transmitter **102** may be designed to optimize signal transfer on an optical spectrum within which the system **100** operates. For example and as will be described below, the transmitter **102** may split a new optical signal (having a signal bandwidth, such as a relatively large signal bandwidth) into two or more slices to fit the optical signal into available channels (each having a bandwidth less than the signal bandwidth). The transmitter **102** may include a processor **108** that handles signal processing and other logic functions, and a memory **110** that stores data usable by the processor **108**.

The receiver **104** may receive the slices of the optical signal and may stitch the slices together to re-form the original new optical signal having the signal bandwidth. In this way, the system **100** increases efficiency of the optical signal transmission by allowing more optical signals to travel along the optical transmission line **106** simultaneously. The receiver **104** may include a processor **112** that handles signal processing and other logic functions, and a memory **114** that stores data usable by the processor **112**.

Disclosed herein are systems and methods for fragmented bandwidth allocation enabled by channel slicing and stitching, as will be described below. Assuming that the current optical spectrum is occupied by multiple data channels with a few relatively small frequency slots available, an incoming optical signal or channel (S) may have a large bandwidth that cannot be accommodated by any single currently available frequency slot without introducing severe inter-channel interference (ICI) from spectrum overlapping. However, the total bandwidth of the separate available frequency slots may be larger than that of the new incoming channel S. In this case, the new incoming channel S can be sliced into two or more spectral fragments, which are then reallocated into the available frequency slots. The detail of this process is described below using a two-slice example. In the beginning, a coherent copy of channel S is generated at another wavelength by nonlinear wave mixing of channel S with a pair of optical frequency comb lines. After channel copy generation, an optical filter may be employed to slice partial spectra of the two channels. It is noted that the combination of the two output channel slices (S1 and S2) should preserve all the information of the original channel S. Then, S1 and S2 may be sufficiently narrow to be inserted into the two available frequency slots for transmission.

Referring to FIGS. **2** and **3**, methods **200** and **300** for transmitting an optical signal through a multiple discrete channels and reconstructing the optical signal, respectively, are shown. The methods **200** and **300** may be performed by a system, such as the system **100** of FIG. **1**.

In block **202**, at least two available channels may be identified in an optical spectrum within which optical transmission may occur. For example and referring to FIG. **4**A, signals on an optical spectrum **400** may be transmitted along a transmission line, such as the transmission line **106** of FIG. **1**. The optical spectrum **400** may include existing signals **401** along with a first channel **402** having a first bandwidth **403** and a second channel **404** having a second bandwidth **405**.

Returning reference to FIG. **2** and in block **204**, a request may be received for a new optical signal to be transmitted on the transmission line. The new optical signal may have a bandwidth that is greater than any of the available channels. For example and referring to FIGS. **4**A and **4**B, a request may be received for a new optical channel **430** to be transmitted along with the existing signals **401**. The new optical signal **430**, however, has a signal bandwidth **432** that is greater than either of (or both of) the first bandwidth **403** and the second bandwidth **405**.

Returning reference to FIG. **2** and in block **206**, the new optical signal may be amplified. The new optical signal may be amplified using any existing amplification technique.

In block **208**, at least two optical frequency comb lines may be generated. The optical frequency comb lines may be selected and amplified as well in this block.

In block **210**, at least one coherent copy of the new optical signal may be created by passing the new optical signal and at least two optical frequency comb lines through a nonlinear device such as periodically poled lithium niobate (PPLN) waveguide to preserve the phase of the optical signal in the copy. The comb lines may be created that are separated by a frequency differential between the available channels in which the new optical signal will be transmitted.

For example and referring to FIG. **4**C, a copy **450** of the new optical signal **430** may be created by wave mixing the new optical signal with the two comb lines. The first comb line **431** and the second comb line **451** may be spaced apart by the spacing frequency **456**, which enables the copy **450** of the new optical signal **430** being automatically spaced apart by a spacing frequency **456** that is equal to a frequency differential **406** between a first channel **402** and the second channel **404**.

Returning reference to FIG. **2** and in block **212**, the new optical signal and the copy (or copies) of the new optical signal may be split into at least two signal slices that each include different portions of the new optical signal. For example and again returning reference to FIGS. **4**A and **4**C, the new optical signal **430** may be sliced to form a first slice **452** that is capable of fitting in the first channel **402**, and the copy **450** may be sliced to form a second slice **454** that fits within the second channel **404**. A bandwidth **453** of the first slice may be selected to be equal to or less than the bandwidth **403** of the first channel **402**. Likewise, a bandwidth **455** of the second slice **454** may be selected to be equal to or less than the bandwidth **405** of the second channel **404**. In that regard, selection of the quantity and location of slicing of the new optical signal **430** may be performed based on the quantity of available channels in the optical spectrum and their corresponding frequencies.

Returning reference to FIG. **2** and in block **214**, the signal slices may be transmitted along the transmission line along with the existing signals. For example and referring to FIG. **4**D, the existing channels **401** along with the first slice **452** and the second slice **454** are transmitted along a transmission line **460**. The first slice **452** is inserted into the first slot **402** and the second slice **454** is inserted into the second slot **404**.

To reconstruct the original new optical signal S at the receiver, the two channel slices S1 and S2 may be first selected from the current wavelength-division-multiplexing (WDM) system. Then, another stage of comb-based wavelength conversion may be employed to recombine S1 and S2 in phase for channel recovery. Because of non-ideal filtering in both stages of spectrum filtering and slice selection, S1 and S2 may have a partially overlapped spectrum, which can then produce inter-symbol interference (ISI). However, the effect of ISI can be readily compensated by a digital linear equalizer afterwards and the original new optical signal S can ultimately be recovered. Note that this channel slicing and stitching technique is scalable to more than two slices simply by generating more copies of the original data channel and by following the methods **200**, **300** shown in FIGS. **2** and **3**.

Turning now to FIG. **3**, the signals from the optical spectrum may arrive at the receiver in block **302**. The signals may include the signal slices that correspond to the original optical signal.

In block **304**, the comb lines may be received at the receiver, or generated at the receiver based on the spacing frequency (for example, the receiver may receive or otherwise become aware of the spacing frequency). In block **306**, the slices may be selected from the optical spectrum. For example, the slices may be selected from the WDM system such as, for example, via filtering. Referring briefly to FIG. **4**E, the slices **452**, **454** may be separated or removed from the optical transmission line.

Returning reference to FIG. **3** and in block **308**, the signal slices may be amplified using any amplifier known in the art. Meanwhile, the comb lines may also be amplified. In block **310**, the signal slices may be stitched together based on the spacing frequency and using the original or new comb lines. In some embodiments, the signal slices may be stitched together using techniques other than comb lines.

Referring again to FIG. **4**E, some overlap **472** may exist between the signal slices **452**, **454**. However, after at least one of equalization or another filtering technique, a stitched version **470** of the original optical signal may have relatively little noise and may be used as the original signal.

As described above, a key function to achieving fragmented bandwidth allocation is channel slicing and stitching. FIG. **5** below illustrates a single-channel experimental setup used to demonstrate operation of such slicing and stitching. After discussion of the exemplary system **500**, results of experiments using the system **500** will be provided.

The system **500** may include a transmitter **502** and a receiver **590**. The transmitter **502** may include a laser **501** and a quadrature signal (IQ) modulator **502**. The IQ modulator **502** may be, for example, a 20/28 Gigabaud (Gbaud) quadrature phase shift keying (QPSK) modulator, a 20 Gbaud quadrature amplitude modulation (QAM) modulator, or the like. The laser **501** may generate a light source which may pass through the IQ modulator **502**, which may output a new optical signal **504** (corresponding to the signal (S)). In some embodiments, the new optical signal **504** may have a wavelength of 1542.53 nanometers (nm) and may have a pulse or other shape.

The new optical signal **504** may pass through an amplifier **506**, which may have a power of 0.15 W. The new optical signal **504** may then pass through a 1 nm filter **508**.

Simultaneously, a comb source **510** having a 20 GHz repetition rate may be generated by a motor locked laser (MLL). A spatial light modulator (SLM) filter **512** may be used to select two comb lines. For example, the comb lines may have wavelengths of 1538.9 nm and 1539.86 nm. The difference in wavelength between the 2 comb lines may correspond to the wavelengths shift of the copy of the new optical signal **504**. The two comb lines may then pass through a preamplifier **514** and a 2 nm filter **516**, which may output the 2 pre-amplified comb lines **518**. The comb lines **518** may then pass through an amplifier **520** that has a power of 0.4 W and may then pass through another 2 nm filter **522**. A copy of the 2 comb lines **518** may also be transmitted to the receiver **590**.

After amplification, the combination of the new optical signal **504** and the selected amplified comb lines **522** may be injected into a PPLN waveguide **524** having a quasi-phase matching (QPM) wavelength of 1541 nm. A copy of the new optical signal **504** may be output by the PPLN waveguide **524**. The copy of the new optical signal may have less power (such as 10 decibels (dB) less power) due to the conversion efficiency.

The new optical signal **504** and the copy may be passed through another SLM filter **526** to cut a left slice from the original optical signal **504** and a right slice from the copy of the signal. The slices of the optical signal **504** and the copy are then transmitted to the receiver **590** via an optical channel **528**. The bandwidths of the optical channel used in the experiments were 27 GHz and 18 GHz. The optical channel **528** used in the experiment was a 10 kilometer (km) long single mode fiber (SMF) channel. In some experiments, the slices were sent directly to channel stitching for reconstruction for comparison with the slices that were transmitted along the optical channel **528**.

At the receiver **590**, the slices are received by an amplifier **532** and amplified. The amplifier **532** may be a 0.06 W amplifier. The slices may then be passed through a 1 nm filter **534** before being rejoined with the comb lines. The comb lines may pass through a 0.5 watt amplifier **536** and a 2 nm filter **538** prior to combination with the slices.

After the slices and comb lines have been rejoined, they pass through a second PPLN waveguide **540** having the same QPM wavelength as the first PPLN waveguide **524**. The first slice is shifted to the right with a conversion efficiency of negative 10 dB and recombined with the second slice. Because the second slice was originally about 10 dB below the first slice, the first slice and the second slice may have similar power amplitudes during recombination. Due to nonideal filtering, the two slices may have approximately a 5 GHz partial spectrum overlap. As a result of the overlap, tuning of the phase offset ($\Delta\varphi$) between S1 and S2 in SLM-2 can lead to constructive ($\Delta\varphi=0$) or destructive ($\Delta\varphi=180$ degrees) channel stitching.

After passing through the PPLN waveguide **540**, the stitched signal may pass through a 1 nm filter **542** before being received by a coherent receiver with channel equalization **544**. Based on a conventional decision-directed algorithm, digital channel equalization with 11 taps was used to remove spectrum-overlapping-induced ISI. If the amount of spectrum overlap increases, more taps might be required to compensate for the increased ISI.

The receiver **544** is a coherent optical receiver which requires a local laser **548** to beat the incoming signal after **542** with the same polarization by tuning the polarization controller **546**.

Referring to FIGS. **5** and **6**A, the combination of the new optical signal **608** and the comb lines **602**, **604** at a location **523** is shown. As shown, the comb lines **602**, **604** are separated by the spacing frequency **606**.

Referring to FIGS. **5** and **6**B, the output of the PPLN waveguide **524** as shown at a location **525**. As shown, the PPLN waveguide **524** outputs the 2 comb lines **602**, **604** along with the new optical signal **608** and the copy of the optical signal **610**. The new optical signal **608** and the copy of the optical signal **610** are separated by the spacing frequency **606**. Furthermore, the copy of the optical signal **610** is approximately 10 dB less in power than the new optical signal **608**.

Referring to FIGS. **5** and **6**C, the output of the SLM filter **526** is shown at a location **527**. As shown, the SLM filter **526** outputs the left slice **612** and the right slice **614**.

Referring to FIGS. **5** and **6**D, the signal that includes the slices **612**, **614** and the comb lines **602**, **604** at a location **539** is shown. The comb lines **602**, **604** are used to move the left slice **612** over to the right slice **614**.

Referring to FIGS. **5** and **6**E, the slices have been stitched together to create a stitched version of the new optical signal **650**. The signal shown in FIG. **6**E is detected at a location **543**. The stitching performed as illustrated in FIG. **6**E is constructive stitching.

Referring to FIGS. **5** and **6**F, the slices have been destructively stitched together to create a stitched version of the new optical signal **652**. The signal shown in FIG. **6**F is detected at the location **543**. Referring to FIGS. **6**E and **6**F, the stitched signal **650** using constructive stitching may be preferable to the stitched signal **652** using destructive stitching.

It is to be noted that in FIG. **6**A, the input optical signal includes both the fundamental band and side lobes. The peak power difference between them may be greater than 15 dB, and no significant contribution of the side lobes to the signal quality is observed. Therefore, the output signal may be allowed to primarily be composed of the fundamental band component, and the channel bandwidth may be considered to be the frequency range of the fundamental band component. Moreover, in order to use channel slicing and stitching for the given WDM grid: (i) the bandwidth of the input signal should be greater than the spectral grid spacing; and (ii) the bandwidths of the sliced signals should be less than the spectral grid spacing.

Referring to FIGS. **7**A through **7**D, constellation diagrams of a 20 Gbaud QPSK channel with 30 dB OSNR under different scenarios are shown. In particular, FIG. **7**A illustrates a back-to-back (B2B) baseline without channel slicing and stitching. FIG. **7**B illustrates detection of only the left channel slice. FIG. **7**C illustrates detection of only the right channel slice. FIG. **7**D illustrates back-to-back (B2B) (i.e., no transmission line) with channel slicing and stitching. FIG. **7**E illustrates the stitched signal after a 10 km transmission with channel slicing and stitching.

Compared to a B2B baseline shown in FIG. **7**A, FIGS. **7**B and **7**C indicate that the channel quality may deteriorate if only a partial spectrum is detected. The different constellations between the left and right slices may be the result of unequal bandwidths of the two slices. FIG. **7**D illustrates that the channel may be successfully recovered after channel stitching of the left and right slices. The signal quality is almost preserved after the 10 km transmission, as shown in FIG. **7**E, because the channel equalization at the receiver also compensates for chromatic dispersion.

Referring again to FIG. **5**, the system performance is further evaluated by tuning the relative phase offset ($\Delta\varphi$) and relative amplitude ($\Delta\alpha$) between the left slice and the right slice in the SLM filter **526**. The reason to investigate the impact of phase/amplitude imbalance is because the two parameters could affect the performance of channel stitching.

FIGS. **8**A-**8**C illustrate various features of the stitched signal for a 20 Gbaud QPSK signal by tuning the relative phase offset between two channel slices. FIG. **8**A illustrates constellation diagrams of the stitched signal with channel equalization for various phase differentials. FIG. **8**B illustrates constellation diagrams of the stitched signal without channel equalization for various phase differentials. FIG. **8**C illustrates measured error-vector-magnitude (EVM) with different phase differentials.

As shown in FIGS. **8**A through **8**C, when the phase is aligned ($\Delta\varphi=0$), channel equalization can compensate for the ISI effect due to the partial spectrum overlapping of the left and right channel slices. Channel equalization helps to decrease the EVM from approximately 20% down to approximately 10%, as shown in FIG. **8**C. Additionally, the tolerance of $\Delta\varphi$ can be as large as 150 degrees with channel equalization, whereas the system without channel equalization may fail if $\Delta\varphi$ is 90 degrees.

FIGS. **9**A-**9**C illustrate various features of the stitched signal for a 20 Gbaud QPSK signal by tuning the relative amplitude between two channel slices. FIG. **8**A illustrates constellation diagrams of the stitched signal with channel equalization for various amplitude differentials. FIG. **8**B illustrates constellation diagrams of the stitched signal without channel equalization for various amplitude differentials. FIG. **8**C illustrates measured error-vector-magnitude (EVM) with different amplitude differentials.

In terms of the relative amplitude $\Delta\alpha$, the system with channel equalization may still be operable when $\Delta\alpha$ is 25 dB, whereas an equalization-free system may be incapable of tolerating $\Delta\alpha$ of 20 dB. As a result, digital channel equalization not only enhances the performance of channel stitching by compensating for ISI, but it also increases the system tolerance for phase/amplitude imbalance. Additionally, a lower signal EVM can be obtained if the phase/amplitude imbalance is pre-compensated optically by SLM-2, as shown in FIGS. **8**A and **8**C, and FIGS. **9**A and **9**C. Therefore, (i) channel equalization is included primarily to compensate for ISI; and (ii) the phase/amplitude imbalance is pre-compensated in the optical domain.

FIG. **10**A is a graph illustrating bit error rate (BER) comparison for a 20 Gbaud QPSK system with and without digital equalization, and FIG. **10**B is a graph illustrating BER for B2B transmission and transmission over the 10 km transmission line.

Compared to a B2B baseline system, the optical signal-to-noise ratio (OSNR) penalty of channel slicing and stitching with channel equalization is below 1 dB, as shown in FIG. **10**A. It is noted that for the B2B baseline system, the same channel equalization is used for comparison. In addition, the two nearly overlapping BER curves in FIG. **10**B indicate the system penalty for the 10 km transmission is negligible. For longer-distance transmission, the increased chromatic dispersion, as well as the wavelength-dependent polarization rotation caused by higher order polarization mode dispersion (PMD), could affect the phase alignment among different channel slices. As a result, the performance of channel stitching might be degraded, which may require further investigation.

FIGS. **11**A-**11**D illustrate channel slicing and stitching with 3 channel slices of a 28 Gbaud QPSK channel. FIG. **11**A illustrates the optical spectrum before PPLN waveguide insertion. FIG. **11**B illustrates the optical spectrum after the SLM 2 filter. FIG. **11**C illustrates the optical spectrum after the second PPLN waveguide. FIG. **11**D illustrates channel reconstruction by stitching the three channel slices.

The spectra of the channel slicing and stitching with three channel slices of a 28 Gbaud QPSK channel are shown in FIGS. **11**A-**11**C, while the corresponding separate channel slices and reconstructed channel constellations are shown in FIG. **11**D. Thus, FIGS. **11**A-**11**D illustrate that slicing and stitching to fit new optical signals into optical transmission lines operates well for more than two slices.

FIG. **12** illustrates BER curves of the 28 Gbaud QPSK system with two and three channel slices. It can be seen that the system performance does not strongly depend on the number of channel slices, and less than 1 dB OSNR penalty is observed compared to the B2B baseline.

FIG. **13**A illustrates EVM comparison between B2B and channel slicing and stitching for a 20 Gbaud 16QAM signal, and FIG. **13**B illustrates BER comparison of the two. FIGS. **13**A and **13**B illustrate that the above-disclosed scheme may be extended to a 20 Gbaud 16QAM signal. Less than 1.5% EVM deterioration with 30 dB OSNR is observed, as shown in FIG. **13**A. Compared to the QPSK scenario in FIG. **13**A, a larger OSNR penalty is observed for 16QAM in FIG. **13**B. A possible reason could be that high order QAM signals are more sensitive to any distortion introduced by nonlinear-wave-mixing-based wavelength conversion.

The application of channel slicing and stitching to enable fragmented bandwidth allocation is experimentally demonstrated in a WDM system with 6 QPSK channels of 20 Gbaud. FIG. **14** illustrates an exemplary system **1400** for channel slicing and stitching in a WDM environment. The central wavelengths of the 6 channels are 1541.68, 1542.00, 1542.16, 1542.32, 1542.52, and 1542.87 nm. Compared to the single-channel experiment shown above, a stage of WDM channel generation is added, as shown by the dotted box **1402**. In this case, an attenuator **1406** is used to adjust the power of the WDM channels, in order to make it similar to that of the added optical channel S **1404**.

After the attenuator, a polarization controller **1408** is used to align the polarization of the WDM channels with that of channel S **1404** in order to maximize the ICI effect. The optical spectra before and after fragmented bandwidth allocation are shown in FIGS. **15**A and **15**B, in which the two sliced channels each have approximately 22 GHz optical bandwidth. At the receiver **1410**, an extra SLM filter (SLM-3) **1412** is used for channel-slice selection and amplitude/phase adjustment. In order to allocate the same power into the two frequency slots, the channel slice with higher power is attenuated by 10 dB in SLM-2 **1414** to offset the effect of the −10 dB conversion efficiency in PPLN-1 **1416**. Subsequently, the power difference is adjusted in SLM-3 **1412** before channel stitching in PPLN-2 **1418**.

The constellation comparison is shown in FIGS. **16**A-**16**D. Compared to direct channel insertion shown in FIGS. **16**C and **16**D, where the entire channel S is inserted into either Slot-1 or Slot-2, fragmented bandwidth allocation can effectively avoid channel spectrum overlapping and therefore suffer much less ICI penalty. The reason for signal quality deterioration in FIG. **16**B compared to the single-channel scenario in FIG. **16**A might be attributed to non-ideal filtering for selecting channel slices, which includes the residual spectra from adjacent channels.

For further system evaluation, BER measurements of the added channel S are presented in FIG. **17**. Compared to direct channel insertion, fragmented bandwidth allocation has more than 6 dB OSNR improvement at a BER of 1e-3. There is an additional OSNR penalty of channel slicing and stitching compared to the single-channel scenario. Similarly, a possible reason for this penalty could be that the filter for selecting a desired channel slice is not significantly sharp to reject the adjacent channels.

This disclosure experimentally demonstrates a reconfigurable channel slicing and stitching for an optical signal to enable fragmented bandwidth allocation without O-E-O conversion. In a 6-channel WDM system, a 20 Gbaud optical channel is successfully reallocated into two fragmented frequency slots and reconstructed at the receiver. Although this scheme is demonstrated for an optical channel that is not pulse shaped, it is believed that the scheme is also applicable to channels that are pulse shaped, e.g., Nyquist shaping.

In the experiments, various issues may degrade system performance, including: (i) the power of the optical signal is attenuated by the loss of different equipment, such as the PPLN (~5 dB insertion loss) and the SLM filter (~6 dB insertion loss); (ii) nonlinear wave mixing in both stages of the channel slicing and stitching requires sufficient signal power as provided by a 2 W EDFA with a ~6 dB noise figure; and (iii) there are optical components with limited bandwidth. It is noted that there are other approaches that may reduce channel bandwidth to fit into the smaller frequency slot, such as narrow filtering or higher-order QAM signal conversion. They may not suffer the same degradations as the present disclosure, but may introduce other issues.

The reason for using an optical frequency comb instead of independent continuous wave lasers is to ensure phase locking among different channel slices, which is generally required for successful signal recovery at the receiver. In the experiments, the selected comb lines (within a ~10-nm spectrum range) have a similar OSNR of ~30 dB. As the scheme is scaled to more channel slices with larger frequency spacing, the quality of the stitched signal may be affected by different OSNRs of different comb lines. In addition, the same comb source was used for both channel slicing and stitching for ease of experimentation; a more realistic implementation would likely use two independent comb sources, one for the transmitter and one the receiver.

Exemplary embodiments of the methods/systems have been disclosed in an illustrative style. Accordingly, the terminology employed throughout should be read in a non-limiting manner. Although minor modifications to the teachings herein will occur to those well versed in the art, it shall be understood that what is intended to be circumscribed within the scope of the patent warranted hereon are all such embodiments that reasonably fall within the scope of the advancement to the art hereby contributed, and that that scope shall not be restricted, except in light of the appended claims and their equivalents. Where used throughout the disclosure and claims, "at least one of A or B" includes "A" only, "B" only, or "A and B."

What is claimed is:

1. A method for transmitting an optical signal through a first channel to take a first portion of the optical signal and a second channel to take a second portion of the optical signal, the first channel and the second channel being separated by a spacing frequency, the method comprising:

generating multiple comb lines from a comb source;

selecting, using a filter, a first pair of spacing coherent optical frequency comb lines from the multiple comb lines;

nonlinearly mixing the optical signal with the first pair of spacing coherent optical frequency comb lines separated by the spacing frequency to create an optical signal copy that is spaced from the optical signal by the spacing frequency;

filtering a first slice of the optical signal and a second slice of the optical signal copy, the first slice representing a first portion of the optical signal and the second slice representing a second complementary portion of the optical signal;

transmitting the first slice of the optical signal and the second slice of the optical signal through the first channel and the second channel, respectively; and

using nonlinear mixing to combine the first slice of the optical signal with the second slice of the optical signal copy with a second pair of spacing coherent optical frequency comb lines separated by the spacing frequency to recover the optical signal.

2. The method of claim **1** further comprising amplifying the optical signal prior to nonlinearly mixing the optical signal with the first pair of spacing coherent optical frequency comb lines.

3. The method of claim **1** wherein the filter includes a first spatial light modulator.

4. The method of claim **1** wherein nonlinearly mixing the optical signal with the first pair of spacing coherent optical frequency comb lines to create the optical signal copy includes passing the optical signal and the first pair of spacing coherent optical frequency comb lines through a first periodically poled lithium niobate waveguide having a quasi-phase matching wavelength such that a phase of the optical signal is preserved in the optical signal copy.

5. The method of claim **1** wherein filtering the first slice of the optical signal and the second slice of the optical signal copy includes tuning a phase offset between the first slice of the optical signal and the second slice of the optical signal copy based on a desire for the first slice and the second slice to be constructively combined.

6. The method of claim **1** further comprising inserting the first slice of the optical signal and the second slice of the optical signal copy to multiple signal channels for co-transmission prior to using the nonlinear mixing to combine the first slice of the optical signal with the second slice of the optical signal copy.

7. The method of claim **1** wherein using the nonlinear mixing to combine the first slice of the optical signal with the second slice of the optical signal copy includes amplifying the first slice of the optical signal with the second slice of the optical signal copy together with the first pair of spacing coherent optical frequency comb lines.

8. The method of claim **1** wherein using the nonlinear mixing to combine the first slice of the optical signal with the second slice of the optical signal copy further includes passing the separate two slices and the second pair of spacing coherent optical frequency comb lines through a second periodically poled lithium niobate waveguide having a quasi-phase matching wavelength.

9. The method of claim **1** further comprising transmitting the first slice of the optical signal through the first channel and transmitting the second slice of the optical signal copy through the second channel prior to using the nonlinear mixing to combine the first slice of the optical signal with the second slice of the optical signal copy.

10. A method for transmitting a first portion of an optical signal and a second portion of the optical signal through a first channel and a second channel, respectively, the method comprising:

generating multiple comb lines using a comb source;

selecting, using a filter, a first pair of spacing coherent optical frequency comb lines from the multiple comb lines;

identifying, at a transmitter, at least two available channels in an available optical spectrum each having an available bandwidth;

receiving, at the transmitter, a request for a new optical signal having a signal bandwidth that is greater than the available bandwidth of either of the at least two available channels;

nonlinearly mixing the new optical signal with the first pair of spacing coherent optical frequency comb lines separated by the spacing frequency to create an optical signal copy that is spaced from the new optical signal by the spacing frequency;

filtering a first slice of the new optical signal and a second slice of the optical signal copy, the first slice representing a first portion of the new optical signal and the second slice representing a second complementary portion of the new optical signal;

transmitting, by the transmitter, the at least two signal slices to a receiver via a first channel and a second channel;

receiving, by a receiver, the at least two signal slices; and

using nonlinear mixing, at the receiver, to combine the at least two signal slices to recover the new optical signal.

11. The method of claim **10** further comprising:

identifying, at the transmitter, a spacing frequency between each of the at least two available channels;

transmitting, by the transmitter, the spacing frequency to the receiver; and

receiving, by the receiver, the spacing frequency, wherein using the nonlinear mixing to combine the at least two signal slices includes using the nonlinear mixing to combine the at least two signal slices further based on the spacing frequency.

12. The method of claim **10** wherein using the nonlinear mixing to combine the at least two signal slices includes comb-based wavelength conversion using similar comb lines as the pair of spacing coherent optical frequency comb lines.

13. The method of claim **10** further comprising performing channel equalization to reduce inter-symbol-interference of the recovered new optical signal.

14. A system for transmitting an optical signal, comprising:

a transmitter having a comb source configured to generate multiple comb lines and a filter configured to select a first pair of spacing coherent optical frequency comb lines from the multiple comb lines, the transmitter being configured to:

identify at least two available channels in an available optical spectrum each having an available bandwidth,

receive a request for a new optical signal having a signal bandwidth that is greater than the available bandwidth of either of the at least two available channels,

nonlinearly mix the new optical signal with the first pair of spacing coherent optical frequency comb lines separated by the spacing frequency to create an optical signal copy that is spaced from the new optical signal by the spacing frequency,

filter a first slice of the new optical signal and a second slice of the optical signal copy, the first slice representing a first portion of the new optical signal and the second slice representing a second complementary portion of the new optical signal, and

transmit the at least two signal slices onto an optical transmission line; and

a receiver configured to:

receive the at least two signal slices via the optical transmission line, and

use nonlinear mixing to combine the at least two signal slices to recover the new optical signal.

15. The system of claim **14** wherein:

the transmitter is further configured to identify a spacing frequency between each of the at least two available channels and to transmit the spacing frequency to the receiver; and

the receiver is configured to nonlinearly mix the at least two signal slices further based on the spacing frequency.

16. The system of claim **14** wherein the receiver is further configured to nonlinearly mix the at least two signal slices using comb-based wavelength conversion using similar comb lines as the pair of spacing coherent optical frequency comb lines.

17. The system of claim **14** wherein the receiver is further configured to perform channel equalization on the new optical signal to reduce inter-symbol-interference of the new optical signal.

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